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A Rapid Soils Analysis Kit

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Abstract: The ability to determine the construction requirements for soil without the need to conduct laboratory testing is essential to performing a contingency design. Until now, only subjective field analysis techniques satisfied this requirement, and their results fail to provide tangible numeric data that can be used to determine moisture-density and California bearing ratio (CBR) design criteria. This report describes the rapid soils analysis kit (RSAK) developed during the period November 2003– May 2007 under the Joint Rapid Airfield Construction Program. The RSAK includes compact field test instruments that are easily transported to provide an immediate measure of soil moisture, grain size distribution (GSD), and plastic limit. An accompanying software program incorporates the numeric data generated from the soils kit, classifies the soil, and uses multiple regression routines based on a statistical analysis of a large database of soil properties to predict optimum moisture content and maximum dry density for the soil of interest. Built-in, higher order regression equations allow the user to visualize complete moisture-density curves for varying compaction energies as well as soaked and unsoaked CBR as functions of water content for the constructed condition of the soil. The moisture-density curve and CBR strength represent the critical data necessary to enable contingency design and construction of highways and airfields.

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Preface

The tests and results described herein pertain to the U.S. Army AT40 research effort entitled "Material Property Prediction." This research effort is intended to provide predictive technologies for generating soil properties for use in contingency construction operations.

The Material Property Prediction project is a part of the Joint Rapid Airfield Construction (JRAC) program. The JRAC program was a comprehensive, 6-year, demonstration-based research and development program completed by the U.S. Army Engineer Research and Development Center (ERDC) in fiscal year 2007. The JRAC program was sponsored by Headquarters, U.S. Army Corps of Engineers, Washington, DC.

This publication was prepared by personnel from the ERDC Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. The findings presented in this report are based upon internal research and implementation through Army and Joint Forces contingency exercises conducted at Fort Bragg, NC, in July 2004 and at Bradshaw Field Training Area, Northern Territory, Australia, in June 2007 for the JRAC program. The principal investigators for this study were Dr. Ernest S. Berney IV and Ronald E. Wahl, Airfields and Pavements Branch (APB), Engineering Systems and Materials Division (ESMD), GSL. Other ERDC GSL personnel who assisted in the research include Travis Mann, Charles Carter, and Larry Dunbar.

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COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

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Executive Summary

An accurate and expedient means to determine the soil classification is essential for establishing design criteria for rapid airfield construction using the in situ soil. Under a contingency design and construction scenario, only a few hours are available to accumulate necessary ground truth data. Until now, only subjective field analysis techniques (U.S. Army Field Manual 5-410) satisfied this requirement, and these results fail to provide tangible numerical data that can be used to establish the necessary construction criteria for an airfield. To address this need, a small-scale field laboratory kit following a stepwise procedure was developed for the Joint Rapid Airfield Construction (JRAC) program. The field kit consists of laboratory-quality testing instruments that include a microwave, electric balance, sieve shaker, sieves, splitter, grinder, mortar and pestle, plastic limit tool and necessary bowls, and spatulas and scoops to handle the material. These instruments provide a measure of soil moisture, grain size distribution (GSD), and plastic limit (PL). Numerical data generated from these soils tests are inputted directly into a software program that calculates a soil classification using linear regression to convert PL into plasticity index, PI. Using the soil classification, PI, and GSD, the software program uses linear regression routines based on an extensive database of soil properties to estimate optimum moisture content and maximum dry density. Built-in higher order regression equations allow the user to visualize complete curves for Proctor density, as-built California Bearing Ratio (CBR), and soaked CBR for the constructed condition of the soil of interest. The Proctor curve and potential CBR strength data are necessary to establish design criteria for rapid airfield construction.

Moisture contents taken from in situ soil samples establish baseline moisture requirements. Dynamic cone penetrometer data points taken at random locations within the area of interest provide baseline CBR strength data. Initial CBR strength data can determine the structural conditions at the site of interest, whether conditions need modification or are satisfactory as is. If improvement is necessary at the site, knowledge of the in situ soil condition and results from the rapid soils analysis allow the soldier to estimate the potential CBR increase from soil compaction. The complete Proctor curve tells the soldier the water and mechanical effort requirements to bring the in situ soil to a satisfactory CBR strength

condition and the compaction tolerance allowed during construction. All this information can be established within the first few hours of arriving at a site and provides the soldier a level of construction information far superior to that previously available.

1   Introduction

Background

In 2002, the U.S. Army Engineer Research and Development Center (ERDC) began a 6-year comprehensive research, development, and demonstration program entitled Joint Rapid Airfield Construction (JRAC). The JRAC program focused on providing engineering tools and systems to increase the U.S. military's contingency airfield upgrade and construction capabilities. These revolutionary new capabilities will allow the Warfighter to meet Future Force deployment requirements (first brigade in 96 hr, first division in 120 hr, and five divisions in 30 days). These objectives will be met through advancements in site selection technologies, enhanced construction methodologies, and new materials and techniques for rapid soil stabilization. All of these technologies, used either separately or as part of an integrated system, focus on reducing the engineering time line, reducing the manpower requirements, reducing the logistical footprint, and increasing system reliability. The current design aircraft for the JRAC program are the C-130 and C-17.

Objective

The objective of this research was to develop a rapid field capability satisfying the JRAC time line to estimate soil properties for design and construction of soil pavement layers. The challenges to meet this goal were threefold: outfit an assessment team with an expedient field laboratory, collect desirable soil properties from literature and incorporate them into a soil properties database, and develop field-driven correlation software linked to the soil property database to deliver estimated soil properties to the end user.

Scope

This report details the research effort required to produce and implement the rapid soils analysis kit (RSAK). The effort began with a state-of-the-practice literature review of field soil property estimation to determine potential suitability of existing techniques. An exhaustive search was made of existing soil property databases followed by a reduction of the desirable material property data. Regression and analysis techniques were performed to establish algorithms and their necessary inputs to estimate

material construction properties. Once the necessary inputs were determined, an expedient field laboratory system was assembled to obtain the data to populate the regression algorithms. Software was then designed in which to input the field laboratory data to enable rapid soil classification and provide estimated construction design curves.

2 Literature Review

The ability to determine the construction requirements for soil without the need to conduct laboratory testing is tantamount to performing an expedient field design. The most common construction requirements involving soil are optimum moisture content (OMC) and maximum dry density (MDD) as determined from a laboratory compaction or Proctor test (Proctor 1937). The Proctor compaction process requires a minimum of 3 days to complete, from the time a field sample of a specific soil is taken (American Society for Testing and Materials (ASTM) D1557). Military pavement design models require the use of the California bearing ratio (CBR) determined during the compaction process outlined in Army Field Manual (FM) 5-410 (U.S. Army 1992). Inclusion of this test requires an even greater amount of time to generate the necessary data. When considering an expedient design process within JRAC, where the allowable time frame for design is hours, not days, the opportunity to acquire these laboratory-based soil properties is impractical. Therefore, under a military scenario of a rapid soil assessment process, there is a need to correlate the Proctor and CBR response to material properties that can be measured from field data within the allowable time frame.

Several studies have developed correlations between compaction response (OMC, MDD) and soil index properties such as Plasticity Index (PI) (U.S. Army Corps of Engineers (USACE) 1962, Ring and Sallberg 1962, Jeng and Strohm 1976) and grain size distribution (GSD) (USACE 1952, Omar et al. 2003). Each of these studies amassed a large number of soils for which Atterberg index testing, GSD, and compaction data were taken. Using a combination of two or more of the following parameters, Plasticity Index (PI), Liquid Limit (LL) and GSD, correlations were made with respect to compaction data to estimate OMC and MDD. The correlation techniques involved linear or multiple linear regressions to identify the optimal combination of measured properties that best fit the compaction data.

All of the studies used the Atterberg limits within their scope of analysis. This was found to be the most important parameter in determining the compaction characteristics of a soil by providing the greatest reduction in variability relative to any other soil parameter. Further evidence of this

importance is shown in Johnson and Sallberg (1960), where the OMC of a standard Proctor compaction curve can be estimated from just the liquid and plastic limits. Some studies made use of available grain size information obtained from ASTM sieves of varying sizes. Principally, these data were grouped into a single parameter based on an average of percent passing several sieve sizes labeled the fineness average or grain size parameter, and sometimes the analysis included a second parameter based on a unique particle diameter such as D_{50}, D_{10}, etc. The addition of the grain size improved the statistical correlations, but no detailed study was made using all the available grain size data in the regression. The basis of these studies showed that good predictions of OMC and MDD could be made if the plasticity and grain size of a soil can be identified.

Of the reviewed reports, very few, if any, of the data used in the regression development are published within the reports. As such, the developed correlations and the range of soil types for which they are valid are unclear. Many of the reports deal with soils in limited geographical areas or a unique set of soil types to satisfy a specific research need. This limits the usefulness of these correlations for worldwide military operations that require correlating techniques over a broader range of soil conditions.

None of the above-mentioned reports attempts to predict the entire Proctor curve, which is essential for construction estimating. Construction quality control in the field requires knowledge of dry density behavior over a range of moisture contents to provide achievable limits to equipment operators. Identifying the Proctor response can be critical to mission success because of high variability between cohesive and noncohesive soil compaction response (Johnson and Sallberg 1960). Recent research has attempted to predict the entire Proctor curve (Basheer 2001) through the use of a neural network regression approach. This research provided good predictive capabilities, but still lacked the ability to include the CBR strength data necessary for pavement design. Further, the transition of this technology to the field is not well defined. Therefore, the use of existing predictive techniques has not found a place in construction practice on a global scale. Rather, the correlations provide references for small locales to reduce repetitive laboratory testing on similar soils.

Contingency operations can occur anywhere in the world, suggesting a wide variation in soil types that are likely to be encountered. The ability to properly assess the construction properties of soil in a given region will

depend highly on the time in service of the engineering unit performing the soil classification. Because of the frequent turnover of military engineers in modern operations, this is an ideal setting for a correlation technology to compensate for the lack of field experience with soil analysis and use of field classification instruments.

In most commercial scenarios, soil is sampled from the field and readily tested in an available laboratory to determine exact construction requirements because time is not as great an issue. In a military scenario, time is of the essence and, once a desired project is identified, construction is expected to begin immediately. To address this need, correlation technology that is both expandable and systematic is necessary to provide military engineers with the tools they need to handle an increasing demand for contingency construction projects.

This report addresses the needs for a verifiable regression model for prediction of OMC, MDD, Proctor curve shape at varying field energies, and soaked and unsoaked CBR for soils worldwide. Multiple linear regressions fitted from the index properties PL, GSD, and the Unified Soil Classification System (USCS) classification allow reliable and expedient prediction of soil compaction properties for contingency military operations.

3 Data Acquisition and Reduction

Acquisition of soil databases

The soil properties used for correlation development were populated from two primary sources, the U.S. Army Engineer Waterways Experiment Station (WES) Soil Compaction Database (USACE 1999) and the Overseas Airfield Database (USACE 1949). The WES Database contained 120 unique soil entries, and the Overseas Database contained 109 unique soil entries. Each database provided data on one or more individual soils representing all 22 inorganic soil types in the USCS. A summary of the data types obtained from each resource is given in Table 1. These two sources represented the most complete military data sets available for the purpose of performing statistical research.

At the time of the 2004 JRAC demonstration, the development of the software package involved only the use of the WES Database. By the completion of the 2007 JRAC demonstration, the Overseas Database was incorporated, which broadened the capability of the statistical analysis by including soils located exclusively outside of the continental United States.

Data formats for regression

All of the compaction, CBR, and grain size distribution data from Table 1 were represented in a graphical form in the WES Database. All the plasticity, specific gravity, OMC, and MDD values were given in a tabular format. To populate the database of soil properties, including Proctor densities and CBR that vary with moisture content, every moisture-density point in the database for each soil and each energy level was recorded. Since a unique CBR data point was not always available at a specific moisture-density point, the corresponding CBR and soaked CBR values were interpolated from their respective curves and recorded. To tabulate the grain size distribution from the curves given in the WES Database, each grain size curve was approximated by recording the percent passing the 3/8-in., No. 4, No. 10, No. 40, No. 100, and No. 200 sieves.

Data within the Overseas Database were provided entirely in tabular format. While all the soils were tested at the ERDC laboratories, these data

Table 1. Typical data obtained for compaction correlation.

	WES Database	Overseas Database
Optimum Moisture Content (OMC)	✓	✓
Maximum Dry Density (MDD)	✓	✓
Plastic Limit (PL)	✓	✓
Liquid Limit (LL)	✓	✓
CE 12 Proctor Curve	✓	
CE 26 Proctor Curve	✓	
CE 55 Proctor Curve[a]	✓	✓
Soaked California Bearing Ratio (CBR)[b]	✓	✓
Unsoaked CBR	✓	
Grain Size Distribution[c]	✓	✓
Specific Gravity	✓	✓

[a] Only the MDD was obtained for the Overseas Database at a compaction energy of CE 56.25 (old American Association of State Highway Transportation Officials' definition).

[b] Only the soaked CBR at the MDD was obtained for the Overseas Database.

[c] Only the percent retained on the No. 10, No. 40, No. 200, and pan sieves was obtained from the Overseas Database.

histories have, unfortunately, been lost. Tabulated data included the OMC and MDD for the modified American Association of State Highway Transportation Officials' compaction effort, the soaked CBR at the listed optimum conditions, the Atterberg limits, and the percent of mass retained on the No. 10, No. 40, No. 200, and pan sieves.

Approach to soils analysis

Analysis of the collected soils data took place over two distinct time frames. A first-generation (G1) analysis took place in the year leading up to the July 2004 JRAC field demonstration. The impending deadline of a deliverable solution to predicting soil properties required the use of an expedited series of statistical analyses, and these were restricted to the inclusion of only the WES Database. Immediately following the demonstration, a second-generation analysis (G2) was undertaken to refine the previous predictive equations and incorporate a larger data set, specifically the Overseas Database. The G1 and G2 analyses were conducted in a similar manner, in that a numerical technique to classify

the soil was developed using the grain size distribution and the PL, followed by prediction of the OMC and MDD, followed by determination of the Proctor curves as a function of soil classification, and lastly, the value of soaked and unsoaked CBR for each soil at varying moisture contents. What differed between the two analyses was the size of the available data set, the identification of specific data trends in the Atterberg limits, the number of variables included in the OMC and MDD regression algorithms, and the inclusion of a multivariate regression algorithm for determining CBR in the G2 analysis.

What follows will be a discussion of the approach taken to solve the immediate problem for the prediction of relevant soil construction properties in the time frame leading up to the 2004 JRAC demonstration. The results of this analysis showed the feasibility of the data analysis, validated the field instrumentation, and provided a sound basis from which to refine the overall technique.

4   Generation 1 Soils Analysis

The G1 soil analysis was begun in the fall of 2003 with the impending deadline of having a functional predictive program by the summer of 2004. This required a rapid assessment of available soils data, determination of basic data trends, and development of a computational system that would allow input of relatively simple field data to populate regression equations that will estimate OMC, MDD, soil classification, and CBR strengths. As discussed earlier, the WES Database was the governing data set during the G1 analysis. To develop the required computational system from field instruments, the following analysis steps were taken:

1. Generate four multivariate regression equations for determination of OMC and MDD for standard and modified Proctor energies for both plastic and nonplastic soils.
2. Generate a regression equation to estimate plasticity index, PI = LL − PL, from the plastic limit for determination of USCS soil classification.
3. From knowledge of (1) and (2), calculate the Proctor compaction curve for standard and modified Proctor energies over a water content range bounded by the data set.
4. From knowledge of (2) and (3), calculate the entire soaked and unsoaked CBR curve over the bounded water content range from (3).

OMC-MDD

The OMC and MDD are important field values that aid the engineer in determining the proper level of soil compaction. The first task in analyzing the data was to develop correlations between the available soil parameters with OMC and MDD. The regression analysis was bounded by data types that could be obtained from rapid field evaluations. It was determined from research on commercially available, small-scale field instruments (see Chapter 6) that only the PL and grain size distribution (GSD) data types could be collected in a compressed contingency time frame. These two tests represented the numerical data available to drive a regression analysis, and both were included in the WES Database. Based upon historical regression analyses (Ring and Sallberg 1962) and in the interest of time, it was decided that a single grain size parameter (GSP) would best represent the grain size data from the sieves, where GSP is the average of

the percent passing by dry weight of each of the six sieves included in the field test kit. The PL would be used directly in the regression.

The OMC and MDD correlations were based upon multiple-linear regressions dependent upon compaction effort (whether standard or modified Proctor energy levels), PL, and the GSP. A matrix of measured OMC and MDD for each soil, along with its associated data, was prepared in a spreadsheet and then imported into MatLab for analysis. Regression algorithms for each parameter—OMC and MDD at standard (CE12) or modified (CE55) effort—were developed by splitting the data by plasticity: cohesive soils with a plasticity index (PI = LL - PL) greater than zero and noncohesive soils with a PI equal to zero.

Equations 4.1–4.8 summarize the equations resulting from the statistical analysis on the WES Database. These equations are grouped according to their compactive effort and the plasticity of the fine fraction of the soil. Listed along with each pair of equations is the number of samples, n, from the WES Database that matched the requirements necessary for regression. It is readily seen that many more plastic data points were available than nonplastic. This is due to the lack of detailed laboratory experimentation typically conducted on nonplastic soils.

1. **CE-12 standard Proctor compaction effort**

   a. For soils with plastic fines (n = 42 samples)

$$OMC~(\%)~=~9.0697~+~0.47874*PL~-~0.1428*GSP \tag{4.1}$$

$$MDD~(pcf)~=~123.04~-~0.98307*PL~+~0.3645*GSP \tag{4.2}$$

   b. For soils with nonplastic fine (n = 19 samples)

$$OMC~(\%)~=~15.038~-~0.096723*GSP \tag{4.3}$$

$$MDD~(pcf)~=~96.556~+~0.47188*GSP \tag{4.4}$$

2. **CE-55 modified Proctor compaction effort**

   a. For soils with plastic fines (n = 58 samples)

$$OMC \ (\%) \ = \ 6.8455 \ + \ 0.36895 * PL \ - \ 0.10135 * GSP \qquad (4.5)$$

$$MDD \ (pcf) \ = \ 131.06 \ - \ 0.84733 * PL \ + \ 0.31392 * GSP \qquad (4.6)$$

b. For soils with nonplastic fines (n = 26 samples)

$$OMC \ (\%) \ = \ 12.247 \ - \ 0.068758 * GSP \qquad (4.7)$$

$$MDD \ (pcf) \ = \ 102.07 \ + \ 0.46044 * GSP \qquad (4.8)$$

Definitions of parameters:

OMC = optimum moisture content (%)
MDD = maximum dry density (pcf)
PL = plastic limit
GSP = grain size parameter
  = $100 - (1/6) * $ (% finer 3/8 sieve + % finer No. 4 + % finer
    No. 10 + % finer No. 40 + % finer No. 100 + % finer No. 200)
R^2 = correlation coefficient

A comparison of the fit resulting from each regression is given in Figures 1–4. The best correlations were found with plastic soils, whose correlation coefficient, R^2, was greater than 0.81 for all cases. This finding is consistent with other published correlations on cohesive soils (USACE 1962, Jeng and Strohm 1976). The lack of detailed studies on the prediction of noncohesive soil response suggests that it is difficult to predict this response. In this study, the nonplastic soils exhibited large variability with a low correlation coefficient. It was decided that the GSP is not sufficient in and of itself to provide a sound correlation; therefore, in the G2 analysis, use of each individual sieve in the regression was undertaken to improve the correlations.

Because of the impending deadline of the 2004 JRAC demonstration, the given equations represented the best available for implementation into a computational system, a software package labeled SoilClassification.exe. Immediately following the demonstration, refinement and improvement of the correlations was begun.

Atterberg limits

Once prediction of the OMC and MDD is complete, determination of any further engineering properties requires knowledge of the USCS soil classification. A USCS soil classification requires the grain size distribution of a soil and the Atterberg limits (ASTM D2487). The RSAK provides for only the grain size distribution and the PL given the 1-hr time frame specified for an expedient soils analysis. The liquid limit, while valuable, requires too much field preparation and execution time, on the order of several hours or days (Lee and Freeman 2007). It has been found that when plasticity data are plotted, trends in response emerge that enable the use of a regression technique to predict the missing LL value.
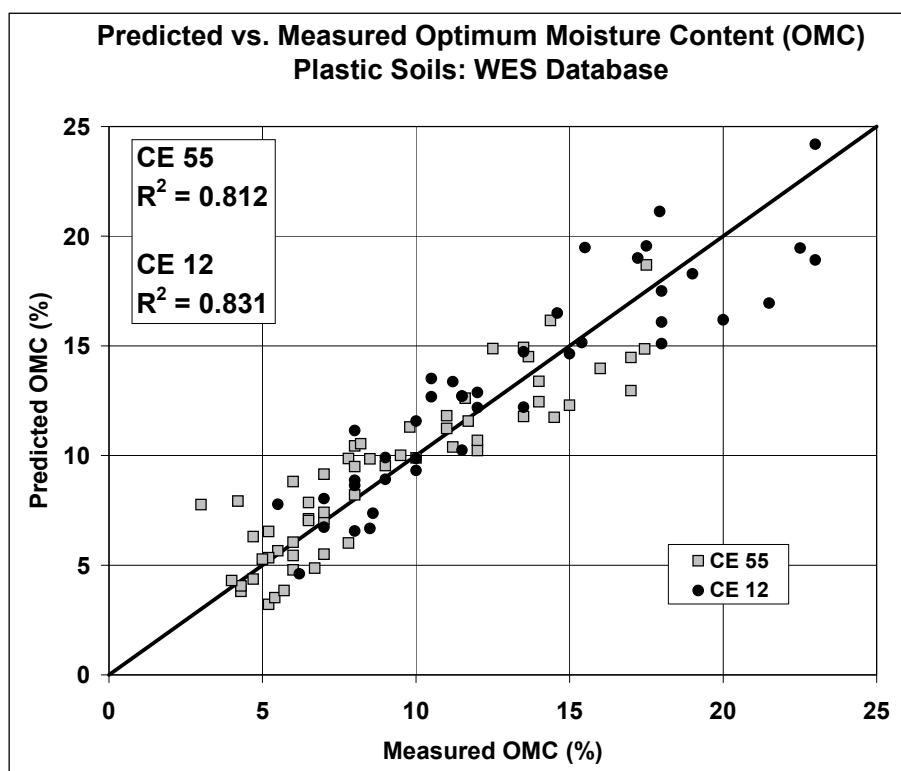
Figure 1. Predicted vs. measured optimum moisture content (plastic soil).
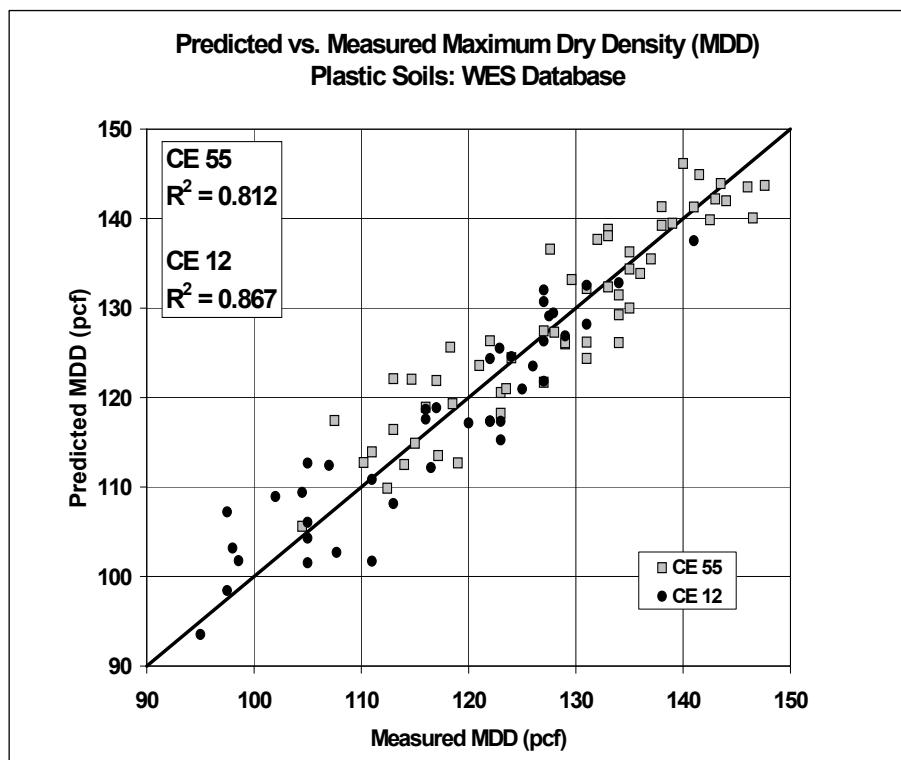
Figure 2. Predicted vs. measured maximum dry density (plastic soil).
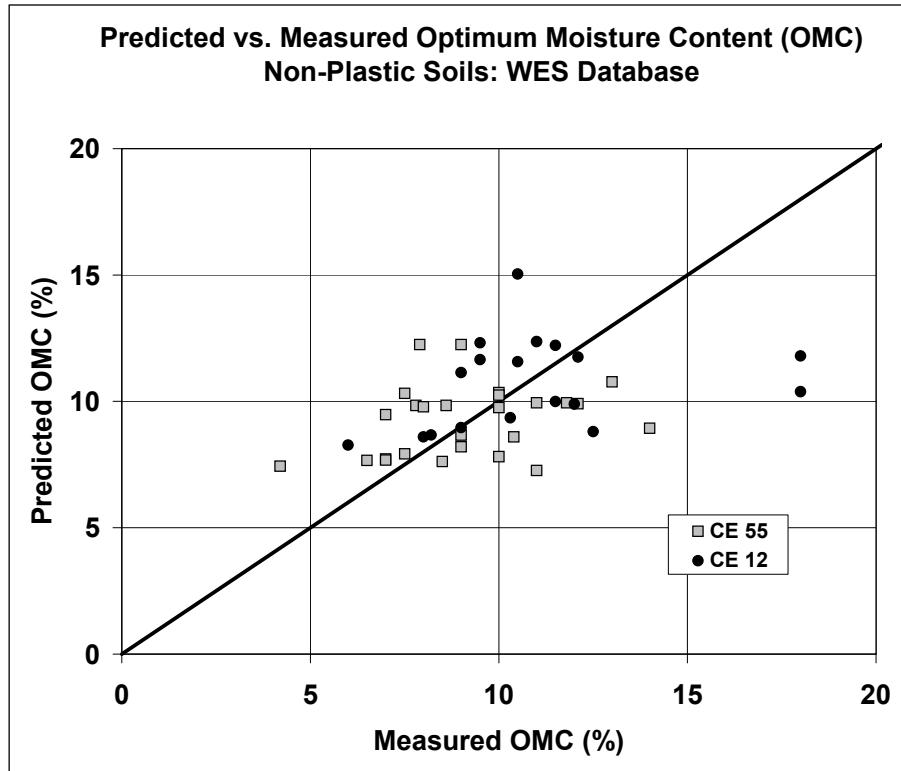
Figure 3. Predicted vs. measured optimum moisture content (nonplastic soil).
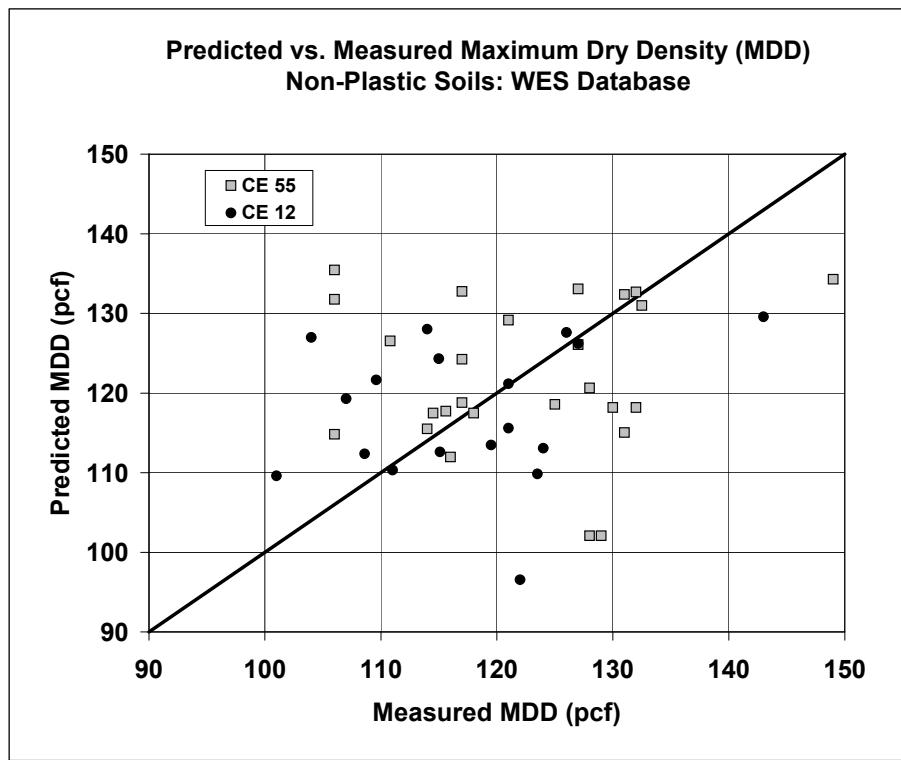
Figure 4. Predicted vs. measured optimum moisture content (nonplastic soil).

Atterberg limit data from the WES Database were tabulated, and a simple linear regression model was generated using the resulting plasticity chart (Figure 5). It can be seen that when all cohesive soils are considered, regardless of the estimated LL, the fines will nearly always be classified as a clayey material with a "C" designation, as the regression line always lies above the A-line. To correct this discrepancy, Figure 6 shows a regression model that differentiates between index properties based on whether the fine content is silty (ML, CL-ML) or clayey (CL, CH) in nature. It can be seen that if a field technique can be implemented to allow a textural interpretation of the plasticity as either silty or clayey, a better approximation of the Atterberg limits is achieved. Based on Figure 5, Equation 4.9 represents the general equation developed to predict LL from PL to aid in USCS soil classification.

$$LL = (PL - 9.1367) / 0.2684 \qquad (4.9)$$

Zero is assumed for the plasticity index in cases in which the expression returns a negative value for LL, or a negative value for PI. This was the chosen model used for evaluation of the material properties during the 2004 JRAC demonstration.
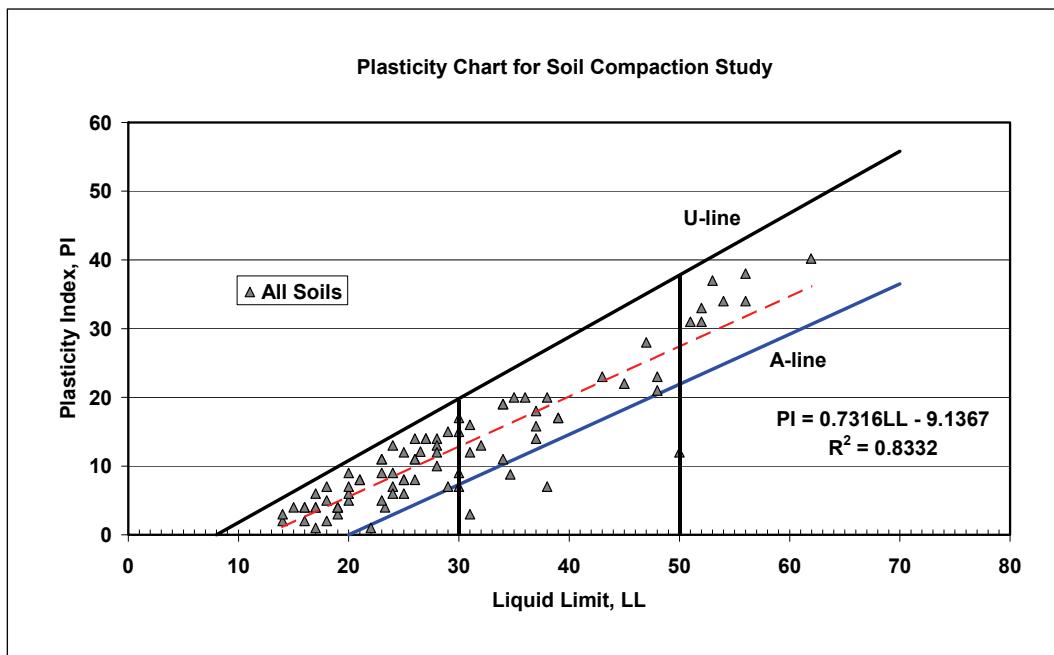
Figure 5. Plasticity chart for WES Database.
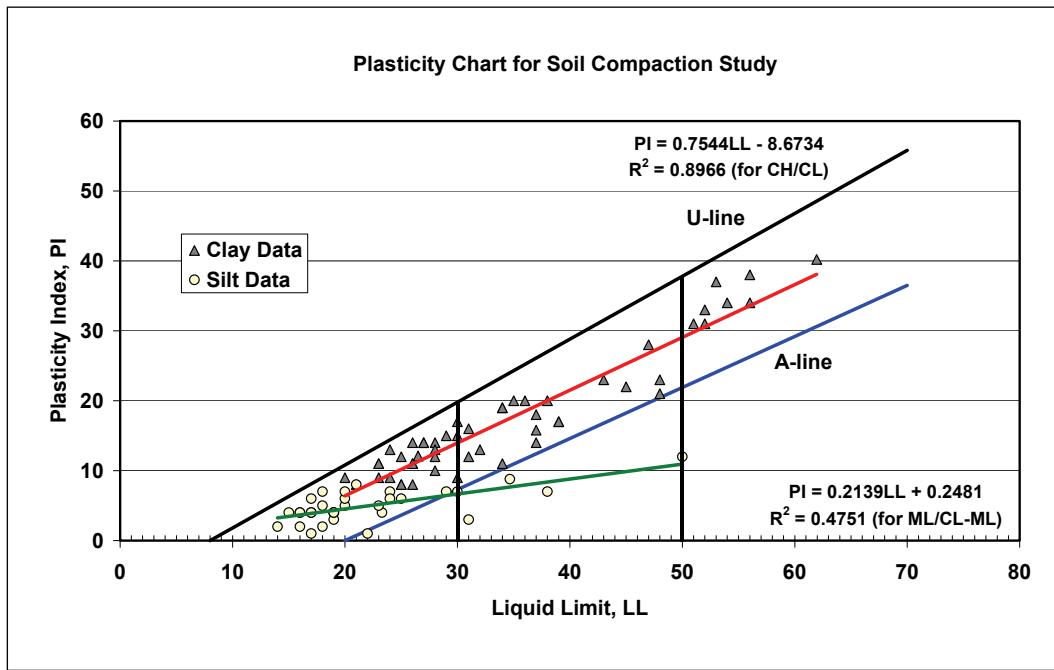
Figure 6. Delineation between clayey and silty soils on WES plasticity chart.

Proctor curves

For each unique soil in the WES Database there exists a series of points lying along both Proctor compaction and CBR curves. Data exist at moisture contents higher and lower than OMC, for both CE-55 and CE-12 compaction energies and soaked and unsoaked CBR. Figure 7 shows the typical
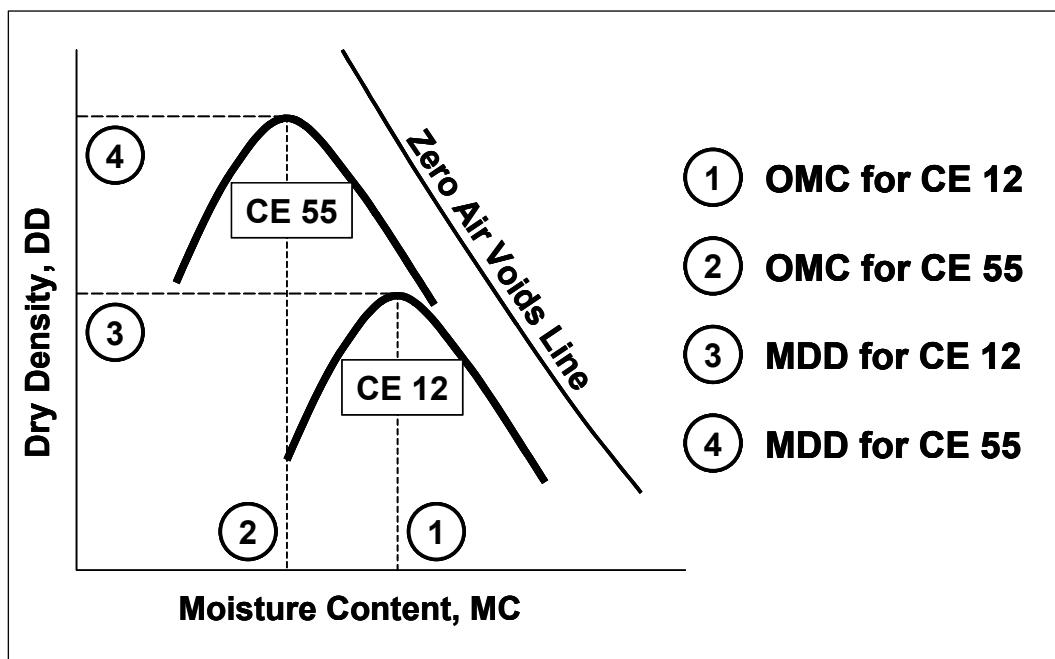
Figure 7. Typical behavior of moisture content-dry density Proctor curves.
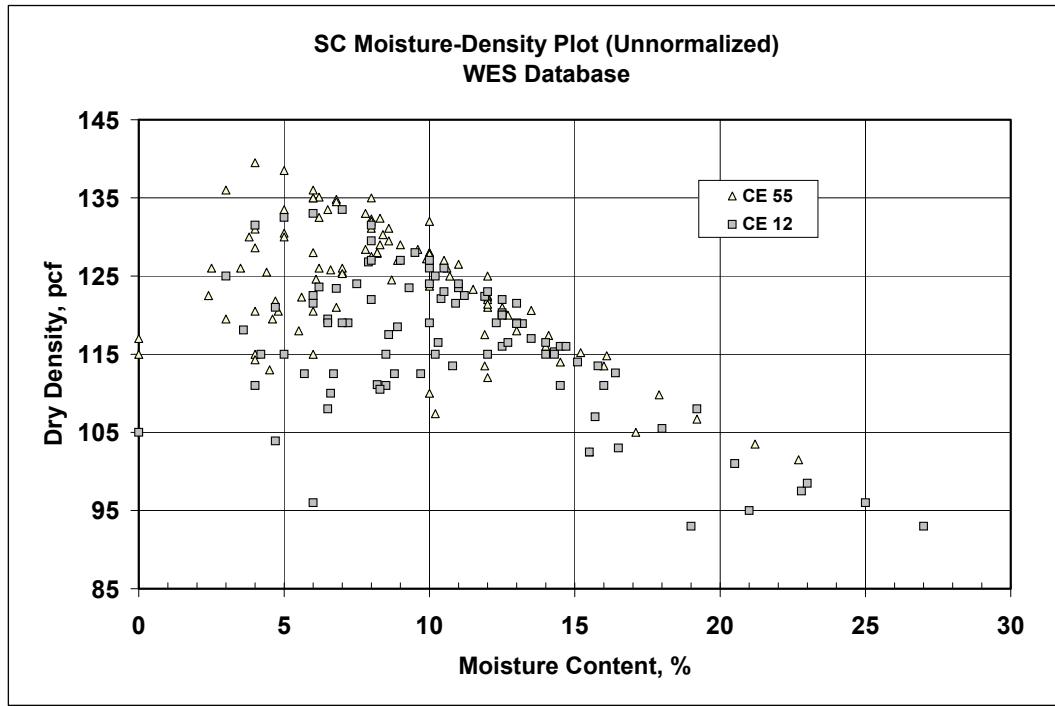
Figure 8. Moisture-density data scatter for an SC soil (WES Database).

shape and behavior of a Proctor moisture-density curve at varying compaction energies. From the WES Database, Figure 8 shows that, when individual compaction curve data from several soils of similar USCS Classification, in this case a sandy-clay (SC), are plotted in a moisture-

density space, there exists considerable variability in the possible OMC and MDD with only slight differences in soil properties.

A simple transformation of the data set was done by normalizing each data point along the two axes as shown in Figure 9. Dry density was normalized as a ratio of the measured dry density (DD) to the maximum dry density (MDD), where the ratio is equal to one at the MDD and less than one at dry densities existing on the wet or dry side of the OMC. Moisture content was normalized as the difference between the measured moisture content (MC) and the OMC, where values less than OMC would take on a negative magnitude and those greater than OMC would be positive. It was found that normalizing the Proctor curve in this manner consolidated all data for a given soil classification into a tight band, with little variance between compaction energies, as shown in Figure 10 for the same range of SC soil.
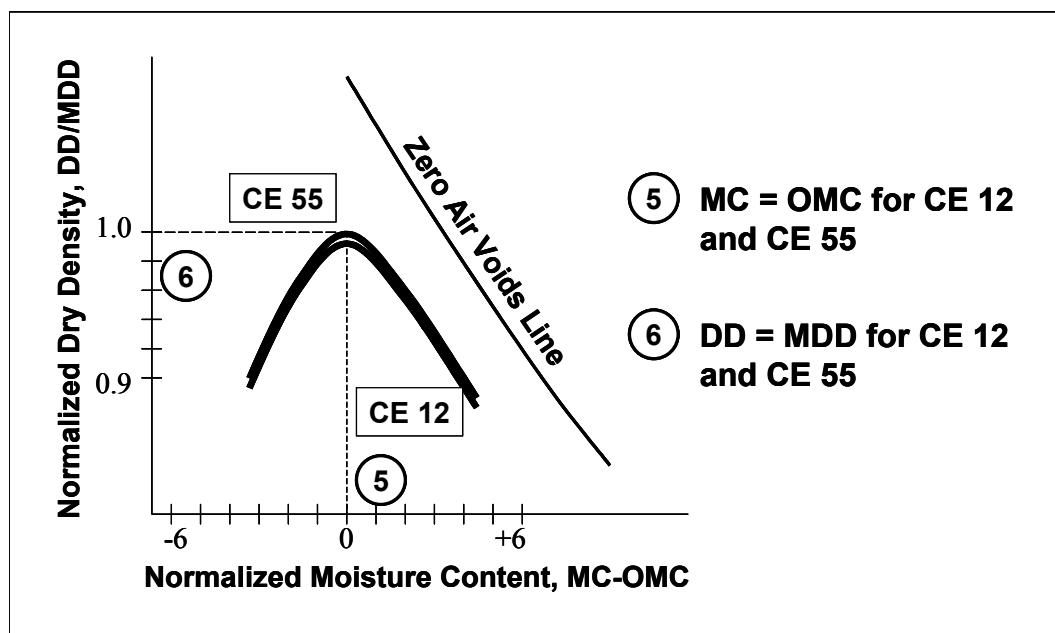
Figure 9. Normalization procedure for Proctor curves at varying energies.

This suggests that, for a given USCS soil classification, the shape of the Proctor curve is well behaved and is essentially independent of compaction level. By defining a normalized compaction curve for each USCS soil classification, the predicted MDD and OMC from the previous regression analysis provide the scaling factors necessary to define a complete Proctor curve for the soil of interest.
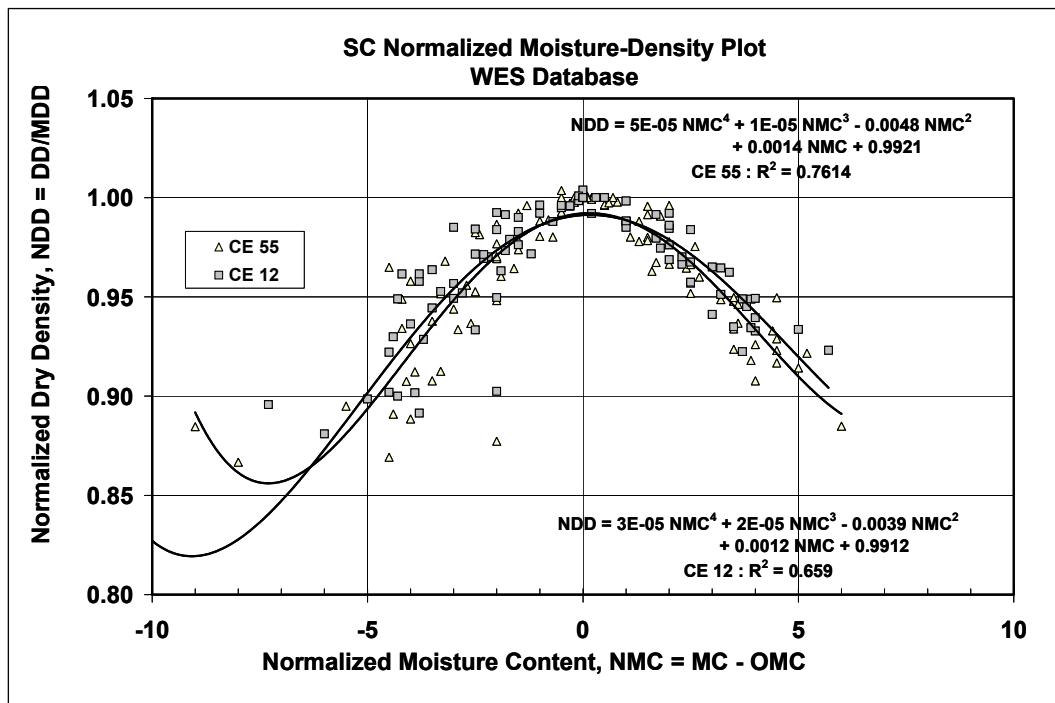
Figure 10. Example of Proctor curve normalization for SC soil (WES Database).

Overlaying the data on Figure 10 is a simple polynomial regression that approximates the parabolic shape of each Proctor curve. A fourth order polynomial expression was selected to best capture the curvature of the moisture-density response shown in Equation 4.10.

$$NDD = a\ NMC^4 + b\ NMC^3 + c\ NMC^2 + d\ NMC + e \qquad (4.10)$$

where

NDD = normalized dry density = DD/MDD
NMC = normalized moisture content = MC − OMC
a, b, c, d, e = empirical coefficients

It was found that gross errors in prediction of dry density occurred when extrapolations of moisture content were made outside the normalized moisture range included in the WES Database. To prevent these erroneous predictions, maximum/minimum criteria were imposed on the range of MC over which the curve was observed to be valid.

It was suggested that both the standard and modified Proctor curves normalize to a similarly shaped curve. However, not all USCS soil types were represented well enough with data to ensure that only one curve could

definitively be used. Therefore, individual regression curves were gener-
ated for each soil classification and compaction energy. Tables of coeffi-
cients for each USCS soil classification fitting the form of the polynomial
expression can be found in Appendix F. No changes were made in defining
the normalized Proctor curves in the second-generation analysis.

CBR curves

Military pavement design requires the use of the CBR. CBR is expressed as
a percentage with properties similar to a constrained modulus, being a
relationship between the modulus of the soil of interest with respect to the
modulus of an idealized base-course material. This test is conducted
in situ to verify existing field strengths as well as in the laboratory on
compacted soil to determine suitability for design. Estimation of this
parameter for design is difficult because CBR is subject to an even a wider
range of variability than that of optimum moisture content and maximum
dry density. Typical charts in published military literature such as
FM 5-410 provide ranges of CBR for soaked conditions at the optimum
moisture content for a variety of USCS soil classifications. This tends to be
a very conservative estimate in contingency design because the soil will
likely not be in a saturated condition at the time of trafficking. For long-
term design, a conservative estimate is reasonable, but long construction
times for permanent pavement systems allow for ample laboratory and
field testing to verify CBR. In a contingency scenario, anticipated CBR
must be known prior to construction to determine design thicknesses and
suitability of borrow material. Further, in a contingency operation, rapid
construction and deployment times do not allow for laboratory testing of
such properties prior to construction. CBR can be estimated once onsite
and validated using a dynamic cone penetrometer during construction to
compare with predicted values.

A contingency tool for predicting CBR has been developed using a regres-
sion technique that makes use of the soils kit field data and the predicted
values of optimum moisture and maximum density to estimate CBR for
any field condition. This will enable the engineer to design for unsaturated
soil strengths that are typically much greater than long-term, saturated
strength. If mission requirements fall within a single season, little change
in the in situ strengths should occur and therefore as-built properties are
critical in minimizing design thickness and maximizing traffic loading.

To tie in field performance with the predicted moisture-density construction curves, CBR data taken at the same moisture-density points used in the OMC-MDD analysis were plotted in a CBR-NMC space. Consideration was taken to create separate CBR predictions for soil in an as-compacted or unsoaked state and in a near-saturated or soaked state. For a given soil from the WES Database, Figure 11 shows a typical CBR-NMC response.
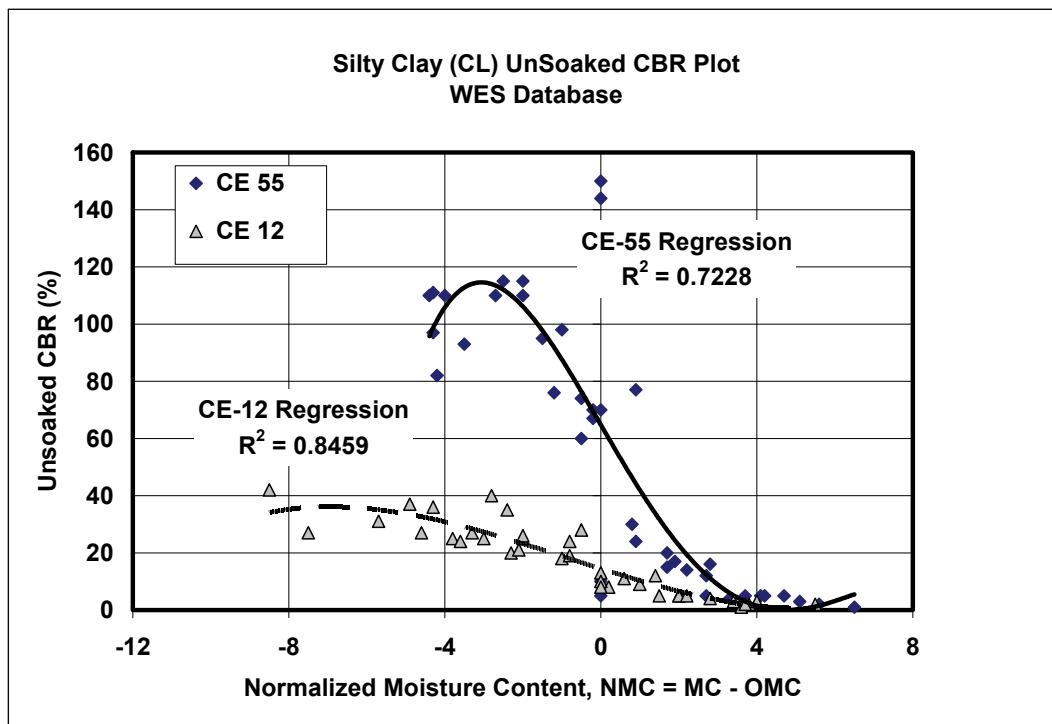
Figure 11. Response of unsoaked CBR in a normalized moisture content space.

The important trends to note in the response of the unsoaked CBR behavior are that the greatest CBR value occurs at a moisture condition slightly dry of optimum (zero on the x-axis), that CBR declines at moisture contents both dry and wet of the peak value, and that CBR becomes asymptotically small at moisture contents much larger than optimum. Soaked CBR response allows prediction of strength loss for situations in which the soil layer is inundated with water. Figure 12 shows an illustration of the normalized CBR-NMC response for the same CL material.

In Figure 12, the trends noted are that peak CBR response occurs at or slightly dry of optimum moisture content (zero on the x-axis), that the strength is markedly reduced from the unsoaked CBR, and that it rapidly
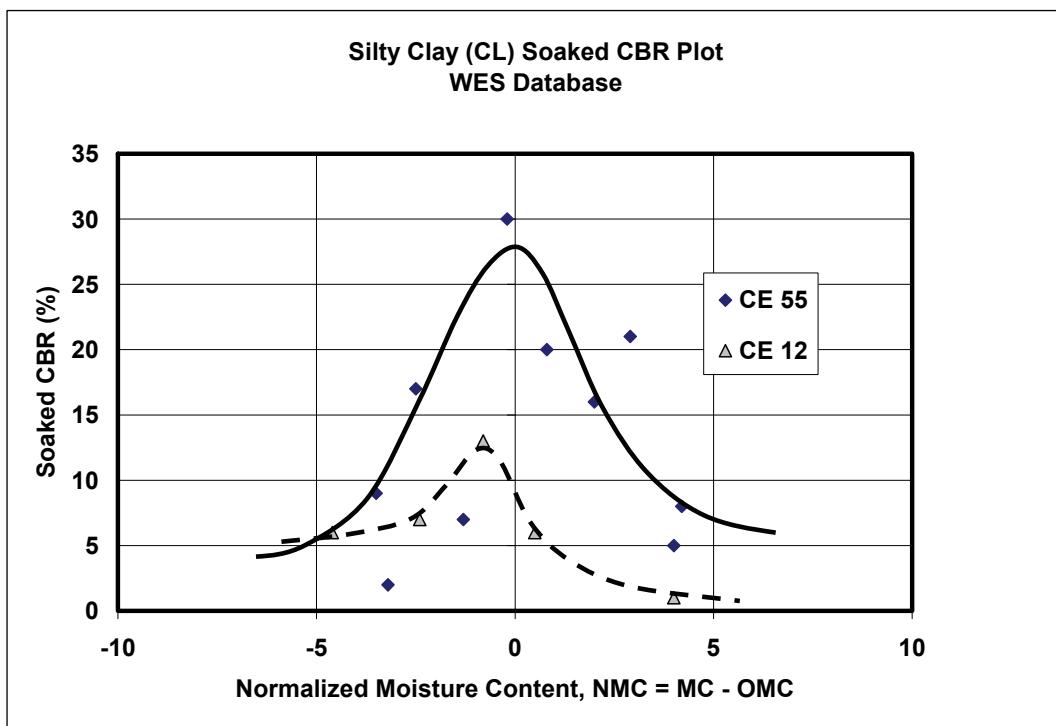
Figure 12. Response of soaked CBR in a normalized moisture content space.

tapers off to small values at relatively small deviations of moisture from the optimum. The importance of these considerations will become more evident in the G2 analysis when determining the statistical behavior of the response in terms of an advanced linear regression model for predicting CBR at a given moisture content.

For many of the soil classifications within the WES Database, the CBR response experienced considerably more variability than the CL material shown above when attempting to normalize response with respect to optimum moisture content. However, the need to estimate structural capacity in the field for design is essential in furthering the state of practice for field analysis techniques. Therefore, in the first-generation analysis, fourth order polynomial curves were fitted to the existing database of CBR properties in the same manner as the Proctor curves shown in Equation 4.11. The coefficients can be found in Appendix F.

$$CBR = a\,NMC^4 + b\,NMC^3 + c\,NMC^2 + d\,NMC + e \qquad (4.11)$$

where

$$CBR = \text{California bearing ratio (\%)}$$
$$NMC = \text{normalized moisture content} = \text{MC} - \text{OMC}$$
$$a, b, c, d, e = \text{empirical coefficients}$$

Not all USCS soil types were represented well enough with data; therefore, individual regression curves were generated for each compaction energy, soil classification, and soaked or unsoaked CBR condition. A bounding range similar to that of the moisture content analysis was adopted to prevent erroneous extrapolation.

5 Generation 2 Soils Analysis

The G2 soils analysis was begun in the fall of 2004 incorporating the Overseas Airfield Database (USACE 1949) as described in Chapter 3. The G1 analysis provided a proof of concept as to the functionality of the analysis tools. Analytic improvements that were identified by the researchers as limitations going into the 2004 JRAC demonstration are now addressed in the G2 analysis. The G2 analysis served to improve on the G1 analysis in the following ways:

1. To expand the applicability of the regression analysis to a broader range of soils and geographical regions through the use of the Overseas Database.
2. To expand the OMC-MDD regression analysis to accommodate each measured sieve value from the known grain size distributions and to normalize predictive response for any compaction energy level.
3. To improve the estimation of PI by noting distinct trends in Atterberg limit response between silty and clayey soils.
4. To generate multivariate regression equations for determination of CBR taking advantage of improved relationships in (2) and (3).

OMC-MDD

With the additional resources of worldwide soil data, the G1 regression equations for both the OMC and MDD were updated to improve the reliability of their estimates. Two series of regression analyses were developed, both changing the form of the regression expressions. The first was using the percentage of soil passing the 3/8-in., No. 4, No. 10, No. 40, No. 100, and No. 200 sieves to maximize the data measured in the RSAK. This improved upon the correlations used in the G1 analysis but was limited to data in the WES Database only. The second used only the percentage of soil retained on the No. 10, No. 40, and No. 200 sieves—being the only grain size data included in the Overseas Database. Instead of using a single GSP for all the sieves included in the instrumentation suite, each of the three available sieve retention percentages was used as a separate variable in the regression. This analysis took advantage of all data from both available data sets. Both procedures improved the correlation fit for prediction of OMC and MDD.

Table 2 shows the resulting outcome of the regression analysis for MDD and OMC predictions. In addition to the introduction of individual sieves as regression variables in the G2 analysis, a parameter to normalize predictions for any compaction energy level was incorporated. This enables the prediction to accommodate ASTM compaction energies (standard and modified) or be customized to specific field equipment energies. The following lists the definitions for the headers and independent variables used in the regression analysis listed in Table 2:

$$LL = \text{liquid limit}$$
$$PL = \text{plastic limit}$$
$$E = \text{energy level (foot-pounds) normalized with respect to CE12 energy (12,000 ft-lb) where CE26 = 26,000 ft-lb and CE55 = 55,000 ft-lb. } \textit{For example, a CE12 soil would have E = 1 and for a CE26 soil, E = 2.17.}$$
$$SieveP = \text{percent passing the 3/8-in., No. 4, No. 10, No. 40, No. 100, and No. 200 sieves}$$
$$SieveR = \text{percent retained on the No. 10, No. 40, and No. 200 sieves}$$
$$G_s = \text{specific gravity}$$
$$\sigma = \text{standard deviation}$$
$$R^2 = \text{correlation coefficient}$$
$$Number\ of\ Soils = \text{number of individual soils tested}$$
$$Number\ of\ Tests = \text{number of data points collected for all individual soils tested (can be greater than number of soils because of energy variations)}$$

In general, when more variables are introduced, a better correlation coefficient is obtained for both plastic and nonplastic soil types. Beginning from the top of Table 2 and working downward, the Atterberg limits for plastic soils account for a large percentage of the variability, with *PL* being the more important of the two. The addition of the energy level and sieve sizes provides a substantial improvement in the correlation. The use of all the sieves (*SieveP*) provides a better correlation than with only the three retained sieves (*SieveR*). However, fewer data points are considered in the *SieveP* analyses and, therefore, a more biased view of the correlation is obtained. For nonplastic soils, the use of the *SieveP* variables was far

Table 2. Regression variables and correlation for plastic and nonplastic soils.

Plastic Soils							
	Number	*Number*	**MDD**		**OMC**		
Case	*Tests*	*Soils*	R^2	σ	R^2	σ	*Independent Variables*
A2	268	156	0.654	8.31	0.699	3.49	PL E
D	191	79	0.837	4.84	0.868	1.72	LL PL E SieveP
D1	191	79	0.780	5.62	0.765	2.30	PL E SieveP
E	268	156	0.823	5.95	0.854	2.43	LL PL E SieveR
E1	268	156	0.769	6.79	0.784	2.96	PL E SieveR
Non-Plastic Soils							
	Number	*Number*	**MDD**		**OMC**		
Case	*Tests*	*Soils*	R^2	σ	R^2	σ	*Independent Variables*
H	70	31	0.724	6.73	0.503	1.99	E SieveP
J	114	73	0.410	9.38	0.180	2.99	E SieveR

superior to the *SieveR* analyses. This suggests that, in the case of nonplastic soils, the lack of a plasticity index restricts the correlation, thereby adding importance to any sieve data available.

For the plastic MDD and OMC response, the best correlation using the largest available soil data set is Case E, which makes use of Atterberg limits, the energy level, and the percent retained on three different sieves. Better correlations are obtained for Case D when using the percent passing all the sieves. However, Case E includes a greater number of worldwide soils and, therefore, is the more general of the two regressions. For the nonplastic case, use of the *SieveP* variables is far superior in correlation, but contains less than half as many data points in the final analysis.

Making use of all the available data taken from the individual sieves and including the energy coefficient reduces the number of required equations from four to two, while maintaining or improving the correlation for all cases from using solely the GSP shown in the G1 analysis. This is the recommended approach given that detailed sieve information is already collected during a field sieve analysis. The form of the finalized regression for prediction of OMC or MDD is given in Equation 5.1.

Table 3 shows the coefficients for the regression equations for each case to predict the OMC and MDD for plastic or nonplastic soils according to Equation 5.1.

$$OMC\ or\ MDD = A*LL + B*PL + C*E + D_1*P3/8\ in. +$$
$$D_2*P4 + D_3*P10 + D_4 + P40 + D_5*P100 + D_6*P200 + \quad (5.1)$$
$$E_1*R4 + E_2*R40 + E_3*R200 + F*GS$$

From the analysis, Cases D1 and E1 are the best in terms of the highest correlation coefficient. If a LL can be performed during the course of the analysis, Case D or E is preferable. Because the *SieveR* variable provides the greatest amount of soils data and therefore includes more of the inherent variability in soil response, Case E is recommended as the ideal regression candidate for predictive analysis.

Table 3. Regression coefficients for RSAK.

CASE	A2		D		D1		E		E1		H		J	
Variable	*MDD*	*OMC*	*MDD*	*OMC*	*MDD*	*OMC*	*MDD*	*OMC*	*MDD*	*OMC*	*MDD*	*OMC*	*MDD*	*OMC*
Constant	144.120	0.345	144.829	3.576	141.285	5.463	139.822	1.586	132.790	5.227	137.892	12.208	120.704	12.289
LL			-0.3473	0.1850			-0.3357	0.1739						
PL	-1.6439	0.7629	-0.7833	0.2746	-1.1300	0.4593	-0.9607	0.4421	-1.3664	0.6522				
E	1.8560	-0.5656	2.2836	-0.7104	2.3705	-0.7568	1.8766	-0.5881	1.9281	-0.6148	-0.0540	-0.2035	-0.1111	0.1298
P3/8			-0.0118	-0.0993	0.0786	-0.1474					0.3934	0.1427		
P4			0.4637	-0.0007	0.2927	0.0904					-0.5850	0.0544		
P10			-0.4898	0.0639	-0.4256	0.0297					-0.1014	0.0008		
P40			-0.0207	0.0277	0.0365	-0.0028					0.0805	0.0071		
P100			-0.1408	0.0582	-0.1627	0.0699					0.1279	0.0562		
P200			0.1030	-0.0363	0.0342	0.0003					1.0210	-0.3839		
R10							0.1238	-0.0345	0.1742	-0.0607			0.1924	-0.0588
R40							0.1543	-0.0702	0.1919	-0.0897			0.0132	-0.0295
R200							-0.0476	0.0133	0.0350	-0.0295			-0.1376	-0.0073

Atterberg limit analysis

Because of the inability to conduct a LL within the compressed time frame, the texture of the fine-grained material is considered to improve the statistical prediction of LL from PL from the G1 analysis. The trends noted in Chapter 4 for predicting the LL from the PL delineating between clayey and silty materials become more evident with the inclusion of low- and high-plasticity silts contained in the Overseas Database (Figure 13). This suggests that a technique to differentiate between these two textural types would enhance the field instrumentation kit and the predictive capability of the soil construction properties. Figure 14 shows the parabolic trends between the two Atterberg limits, making a distinction between clayey and silty texture that improves upon the singular relationship used in the G1 analysis for the 2004 JRAC Demonstration.

Plasticity Chart for WES and Overseas Soils

$PI = 0.7635 LL - 9.7348$
$R^2 = 0.9332$

U-line

A-line

$PI = 0.4678 LL - 5.6335$
$R^2 = 0.8486$

- △ CH/CL
- ○ CL-ML/ML/MH

Plasticity Index, PI
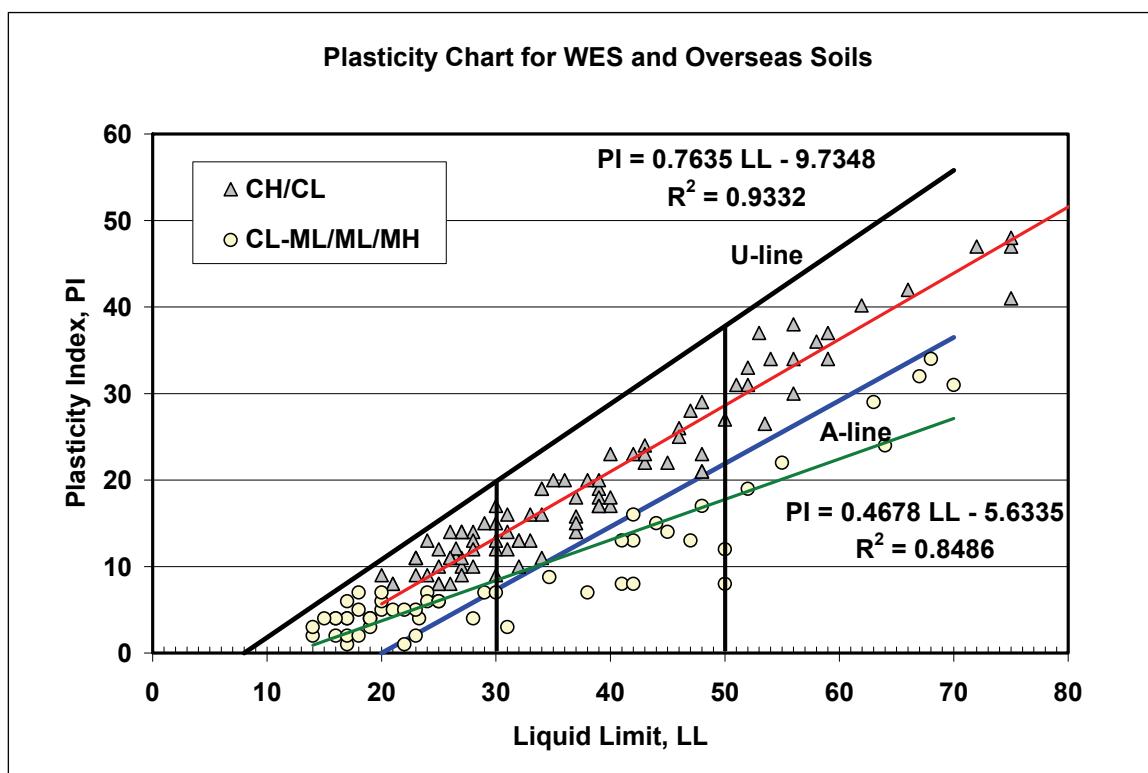
Liquid Limit, LL

Figure 13. Plasticity chart for WES and Overseas Databases delineating clayey and silty soil texture.

Correlation between Plastic Limit to Liquid Limit

ML/MH/CL-ML
$LL = 0.0136PL^2 + 0.9905PL + 1.3067$
$R^2 = 0.882$

CL/CH
$LL = 0.0298PL^2 + 1.4229PL + 1.4724$
$R^2 = 0.6307$

- △ CH/CL
- ○ CL-ML/ML/MH

Liquid Limit, LL
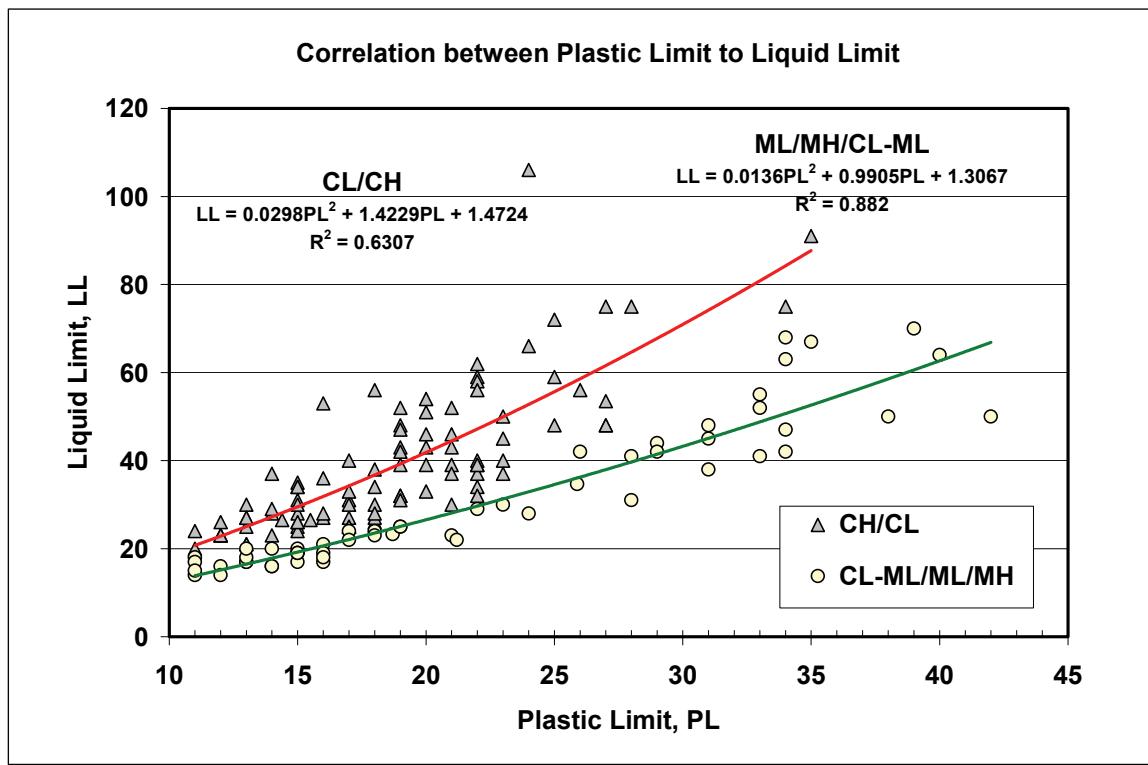
Plastic Limit, PL

Figure 14. Correlation between liquid limit and plastic limit for clayey and silty soil textures.

Proctor curves

No further refinement of the Proctor curve estimation was made owing to the fact that only OMC and MDD data were given in the Overseas Database, which did not influence the shape of the moisture-density response. Therefore, the G1 analysis remains unchanged, and the fourth order polynomial approximation of the normalized Proctor response is recommended.

CBR curves

The most significant refinement of the G2 analysis is the prediction of the CBR value both soaked and unsoaked using a multivariate regression analysis. The Overseas Database provided only soaked CBR values at MDD and therefore contributed little to the overall knowledge base. However, the wealth of CBR data included in the WES Database provided great insight into trends in behavior associated with the CBR.

The G1 approach to analyzing the CBR data from the soils database was to separate all the CBR data by soil classification, which in turn created 22 individual regression curves. This concept followed on the idea that the Proctor curves were unique for each soil type and therefore so, too, would be the CBR curves. While this provided a CBR estimate for each soil type, the data that existed for each soil were far more limited than the available compaction data. Therefore, the correlations were suspect given the limited information and because, in some cases, only data from a single soil sample existed for a given USCS classification, meaning that all future predicted curves would be functions of that single sample.

The G2 analysis did away with the USCS dependent curves and instead attempted to use all available CBR data to provide a more statistically sound approach to predicting the response. In this case, every data point contained in the combined databases was considered. The regression variables were similar to the OMC-MDD analysis in grain size and plasticity, but also included were the current dry density and deviation from the optimum moisture content.

Reduction of data from the CBR test is a more complex process than the compaction response because soil strength does not vary with water content in the same simple parabolic trend as the density. This complexity was addressed by subdividing the data set based on four observed trends

to establish stronger correlation coefficients. The data were separated according to the following criteria.

In a soaked or unsoaked condition (S or U)

CBR strength is strongly associated with the soaked or unsoaked nature of the material. Soaked CBR values are nearly always less than the unsoaked condition and often by an order of magnitude. Division of these two behaviors follows with the G1 analysis.

On the dry or wet side of the OMC (D or W)

CBR reaches a peak value at a moisture content slightly less than the OMC. This is the result of an increase in tensile strength resulting from shrinking water menisci between grains (Berney et al. 2003). At water contents drier than this condition, the strength decreases because of a combination of lower dry density and poorer water distribution in the pore spaces. At water contents wetter than this condition, including OMC, the water menisci relax, reducing tensile strength and resulting in a lower dry density. This phenomenon was noted in both the soaked and unsoaked conditions, but the percentage of OMC at which the peak strength occurred differed. In the soaked (S) condition, the peak was nearly at OMC, falling at approximately 96% of OMC. In the unsoaked (U) condition, the peak strength was found at a much lower value of water content, being 80% of OMC. Data were separated as being drier or wetter than these two OMC conditions.

Had less than or greater than 5% retained on the No. 10 sieve (R10) (L or G)

Strength response varies between coarse-grained and fine-grained soils because of the influence of the fine fraction as it interacts with the water. A study was undertaken to examine the data to identify the break in the grain size at which coarse/fine behavior becomes most apparent. Table 4 shows the R^2 values for the basic groupings as a function of the R10 percentage to determine the optimum correlation. This table indicates that a value of 5% retained on the No. 10 sieve (*R10-5*) is the best proportion to split the statistical sample to represent the strength change from coarse to fine behavior, as reflected in the improved correlation with CBR strength for both soaked and unsoaked conditions.

Table 4. Determination of optimum split for coarse/fine CBR analysis.

R10 %	No. of samples	SWL R^2	SDL R^2	No. of samples	SWG R^2	SDG R^2	Average R^2	
							SW	SD
0	660	0.569	0.456	660	0.569	0.456	0.569	0.456
5	334	0.707	0.495	326	0.599	0.499	*0.653*	*0.497*
10	366	0.680	0.477	294	0.592	0.530	0.636	0.503
30	434	0.632	0.441	226	0.636	0.546	0.634	0.494
40	495	0.641	0.428	165	0.631	0.610	0.636	0.519
50	532	0.619	0.449	128	0.518	0.643	0.569	0.546
R10 %	No. of samples	UWL R^2	UDL R^2	No. of samples	UWG R^2	UDG R^2	Average R^2	
							UW	UD
0	660	0.621	0.720	660	0.621	0.720	0.621	0.720
5	334	0.700	0.840	326	0.614	0.668	*0.657*	*0.754*
10	366	0.697	0.837	294	0.604	0.673	0.650	0.755
30	434	0.693	0.819	226	0.570	0.660	0.632	0.739
40	495	0.694	0.798	165	0.506	0.634	0.600	0.716
50	532	0.681	0.776	128	0.459	0.616	0.570	0.696

Other R10 percentages can be identified in the table that have a larger correlation coefficient than the 5% condition, but when considering both the wet side/dry side and the soaked/unsoaked conditions, the R10-5 split is the best overall indicator of strength change.

Was plastic or nonplastic (P or N)

It was found through observation that using the PI as a separating criterion created slight improvements in the correlation. It is important to note that PI is approximated in the analysis based on regression equations as a function of soil type and PL. Therefore, PL (not PI) is used in the regression to avoid a compounded error in the CBR prediction.

This breakdown of data resulted in a series of 16 equations (24 options) that provided good predictive capabilities for the 1418 CBR data points. Tables 5 and 6 provide summaries of the regression coefficients for square-root and logarithmic analyses, respectively, sample size, correlation coefficient, standard deviation, and sample size for each of the required equations. The CBR relationship is based on the following variables:

$$PL = \text{plastic limit}$$
$$Energy = \text{energy Level (ft-lb) normalized with respect to}$$
$$\text{CE12 energy (12,000 ft-lb) where CE26}$$
$$= 26,000 \text{ ft-lb and CE55} = 55,000 \text{ ft-lb.}$$

For example, a CE12 soil would have E = 1 and for a CE26 soil, E = 2.17.

$R10$ = percent retained on the No. 10 sieve

$R40$ = percent retained on the No. 40 sieve

$R200$ = percent retained on the No. 200 sieve

$P200$ = percent passing the No. 200 sieve

MC-OMC = difference between the moisture content at the measured CBR value and the optimum moisture content of the soil

DD = dry density at the measured CBR

MDD = maximum dry density of the soil

σ = standard deviation (*geometric for log scale)*

R^2 = correlation coefficient

Number of Samples = number of data points used for each regression

Table 5. CBR regression coefficients for square-root analysis.

Square-Root Regressions							
Soaked Conditions							
Variable	SWLP	SDLP	SWLN	SDLN	SWGP	SDGP	SWGN	SDGN
Constant	-3.2642	-19.5750	1.4435	-6.7850	-9.5297	-7.7746	0.0000	0.0000
PL	0.0282	0.1755			0.0442	-0.0088		
Energy	0.0448	-0.2886	0.2580	0.3460	0.4833	0.3360	0.5285	0.5909
R10	0.1347	0.0689	0.1568	1.0565	0.0643	0.0674	-0.0177	-0.0538
R40	-0.0473	0.0202	0.0090	-0.0430	0.0790	0.0896	-0.0782	-0.0435
R200	-0.0285	-0.0052	-0.0142	-0.0071	0.0845	0.1240	0.0103	-0.1059
P200	-0.0187	-0.0089	-0.0370	0.0011	0.0160	0.0200	-0.0925	-0.0067
MC-OMC	-0.3257	0.1401	-0.0677	0.1323	0.0220	0.5024	-0.4594	0.2994
DD	0.0672	0.2302	0.2394	0.2933	0.4054	0.3479	0.4310	0.5856
MDD	0.0049	-0.0347	-0.2018	-0.1778	-0.3568	-0.2887	-0.3628	-0.4741
R^2-value	0.506	0.567	0.671	0.848	0.621	0.654	0.614	0.833
σ	1.117	1.453	0.811	0.756	1.421	1.799	1.433	1.223
# samples	162	86	44	54	125	99	33	34
Unsoaked Conditions							
Variable	UWLP	UDLP	UWLN	UDLN	UWGP	UDGP	UWGN	UDGN
Constant	1.6052	-6.7188	-8.7237	-17.8770	-7.7571	0.0293	0.0000	0.0000
PL	0.0143	0.1116			0.0234	-0.0655		
Energy	0.7143	1.0307	0.4122	0.2691	1.0575	1.2296	0.9855	1.1181
R10	0.0267	0.0166	1.1265	1.0135	0.0454	-0.0022	0.1301	0.0634
R40	-0.0331	-0.0259	-0.0343	-0.0238	0.0479	0.0300	0.0440	-0.0230
R200	-0.0006	0.0017	0.0003	0.0060	0.0384	-0.0155	0.0707	0.0049
P200	-0.0041	0.0075	0.0418	0.0888	0.0140	0.0044	0.0467	-0.0112
MC-OMC	-0.6626	0.1745	-0.2004	0.0938	-1.0130	-0.0239	-0.8077	-0.0894
DD	0.0655	0.0483	0.3380	0.2404	0.3328	0.2235	0.0059	0.4205
MDD	-0.0493	0.0382	-0.2159	-0.0311	-0.2709	-0.1688	-0.0380	-0.3794
R^2-value	0.746	0.858	0.796	0.894	0.712	0.715	0.684	0.822
σ	1.344	0.986	0.782	0.571	2.196	1.736	1.832	1.387
# samples	209	58	46	42	212	118	54	42

Table 6. CBR regression coefficients for logarithmic analysis.

Logarithmic Regressions								
Soaked Conditions								
Variable	SWLP	SDLP	SWLN	SDLN	SWGP	SDGP	SWGN	SDGN
Constant	-0.3950	-11.1380	2.2113	1.0441	-4.8211	-3.7729	0.0000	0.0000
PL	0.0007	0.1086			0.0320	0.0243		
Energy	0.0825	-0.1946	0.1088	0.1835	0.2989	0.0771	0.2424	0.1497
R10	0.0971	0.0314	0.1386	0.5513	0.0370	0.0284	0.0082	-0.0392
R40	-0.0265	0.0096	-0.0033	-0.0233	0.0413	0.0373	-0.0090	-0.0501
R200	-0.0159	-0.0057	-0.0085	-0.0065	0.0474	0.0561	0.0200	-0.0564
P200	-0.0104	-0.0031	-0.0192	-0.0030	0.0112	0.0070	-0.0245	-0.0379
MC-OMC	-0.2144	0.1150	-0.0300	0.0607	-0.0030	0.1915	0.0597	0.1560
DD	0.0658	0.1129	0.1750	0.1396	0.2377	0.1541	0.2871	0.2434
MDD	-0.0338	-0.0010	-0.1614	-0.1157	-0.2150	-0.1219	-0.2669	-0.1720
R^2-value	0.617	0.591	0.663	0.823	0.677	0.671	0.668	0.889
σ	0.608	0.736	0.415	0.372	0.726	0.713	0.502	0.420
# samples	162	86	44	54	125	99	33	34
Unsoaked Condition								
Variable	UWLP	UDLP	UWLN	UDLN	UWGP	UDGP	UWGN	UDGN
Constant	2.5888	0.2744	-0.9243	-4.9255	-2.0629	2.3638	0.0000	0.0000
PL	-0.0014	0.0350			0.0166	-0.0060		
Energy	0.3376	0.2944	0.1555	0.1117	0.4389	0.3103	0.3407	0.2744
R10	0.0394	-0.0029	0.5964	0.4578	0.0205	0.0014	0.0756	0.0379
R40	-0.0142	-0.0038	-0.0196	-0.0106	0.0253	0.0060	0.0407	0.0180
R200	-0.0030	0.0010	-0.0030	0.0016	0.0209	-0.0002	0.0485	0.0247
P200	-0.0037	0.0026	0.0635	0.0556	0.0084	0.0018	0.0367	0.0148
MC-OMC	-0.3426	0.0590	-0.0869	0.0407	-0.4444	0.0218	-0.3244	0.0005
DD	0.0531	0.0082	0.1265	0.0835	0.1576	0.0417	-0.0082	0.0928
MDD	-0.0536	0.0119	-0.0901	-0.0103	-0.1396	-0.0330	-0.0143	-0.0840
R^2-value	0.822	0.877	0.771	0.874	0.800	0.767	0.664	0.811
σ	0.555	0.250	0.325	0.237	0.729	0.361	0.726	0.350
# samples	209	58	46	42	212	118	54	42

It can be seen in Figures 15–18 that either the square root or the logarithm of the CBR value minimized the error of the model, depending on the range of CBR of interest. At low CBR values, the square root approximation (Equation 5.2) provided the least error while, at high CBR values, the logarithmic relationship (Equation 5.3) provided the least error. Both approximations are presented here, and the user can use engineering judgment to decide on the most conservative estimate. For numerical stability, the square root approximation was incorporated into the soils kit analysis software.

$$\sqrt{CBR} = a + b*PL + c*Energy + d*R10 + e*R40 +$$
$$f*R200 + g*P200 + h*(MC-OMC) + i*DD \tag{5.2}$$

$$ln(CBR) = a + b*PL + c*Energy + d*R10 + e*R40 +$$
$$f*R200 + g*P200 + h*(MC-OMC) + i*DD \tag{5.3}$$
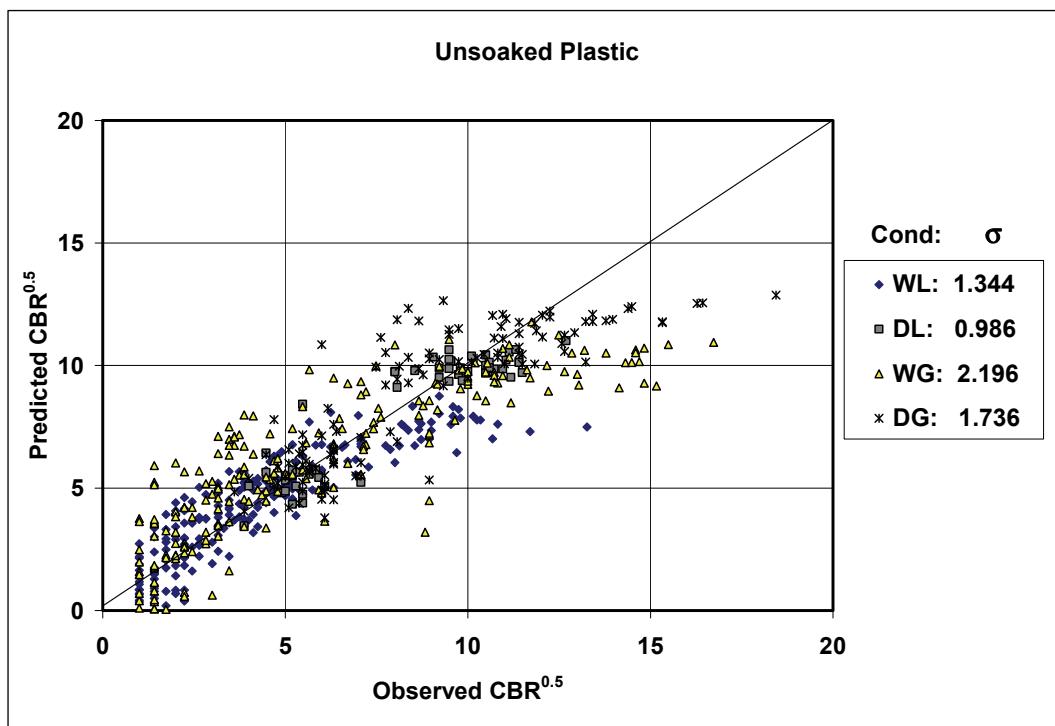
Figure 15. Observed v. predicted $\sqrt{\mathrm{CBR}}$ response for unsoaked plastic soils.
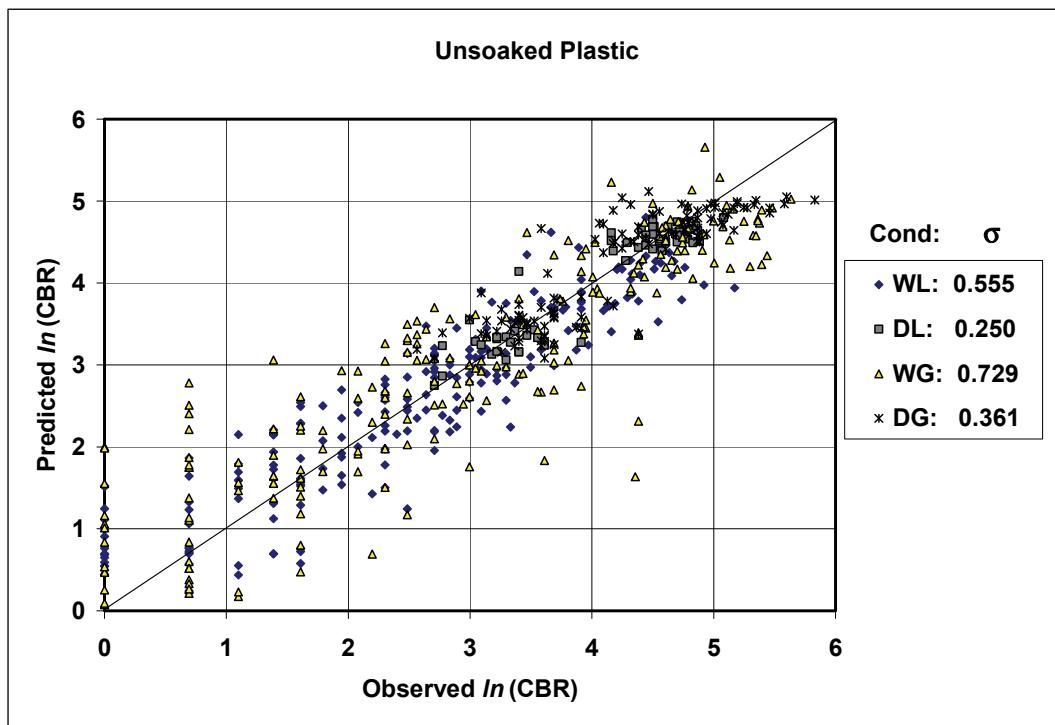
Figure 16. Observed vs. predicted *In (CBR)* response for unsoaked plastic soils.

Figure 17. Observed vs. predicted $\sqrt{\mathrm{CBR}}$ response for unsoaked nonplastic soils.
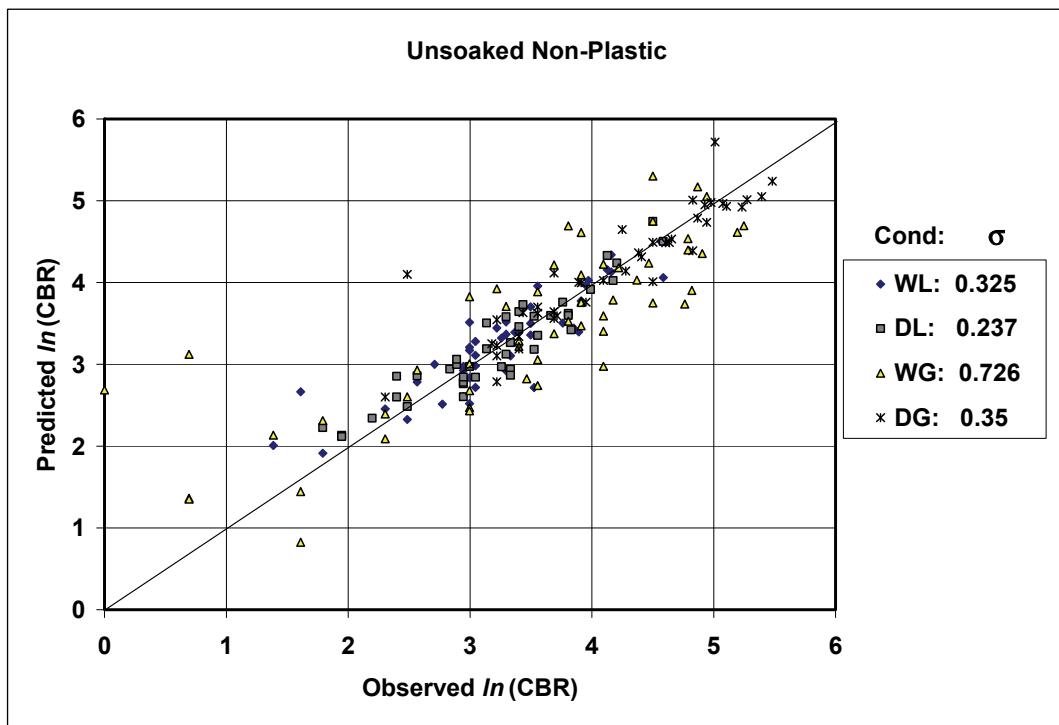
Figure 18. Observed vs. predicted *In (CBR)* response for unsoaked nonplastic soils.

A key advantage of the G2 regression algorithm is its dependence upon the grain size behavior of the soil. This allows a smooth transition of CBR prediction as grain size properties change, even during the transition from one soil classification to another. In the G1 analysis, abrupt changes in CBR would be predicted when soil classifications crossed over from gravels to sands. This occurs because G1 predictions are based solely on available CBR curves in the database as opposed to a prediction using RSAK-collected data. The G2 analysis negates this abruptness and steadily adjusts CBR values throughout the soil classification system.

No natural, in situ CBR strengths were available to use as a guide to the soil conditions prior to construction, as this must be determined onsite through the use of the dynamic cone penetrometer. This analysis will only provide as-built strengths to be used as design inputs to determine maximum aircraft loading and coverage level prior to anticipated failure.

6   Field Instrumentation Suite

An accurate and expedient means of determining the soil classification is essential to establish design criteria for rapid airfield construction using the in situ soil. Under a contingency design and construction scenario, only a few hours are available to accumulate necessary ground truth data. Until now, only subjective field analysis techniques (Field Manual 5-410, USACE 1992) satisfied this requirement, and the results obtained fail to provide tangible numeric data that can be used to establish the necessary construction criteria for an airfield. To provide the necessary input to power the developed regressions, a small-scale field laboratory (the RSAK), following a stepwise procedure, was developed. The RSAK consists of laboratory-quality testing instruments that include a microwave, electric balance, grinder, splitter, mortar and pestle, sieve shaker, sieves, plastic limit tool and necessary bowls, spatulas, and scoops to handle the material (Figure 19) that can be packaged into two large Pelican® cases for transport (Figure 20) (see Chapter 7 for detail). Combined, these instruments provide a measure of soil moisture, GSD, and PL. Numerical data generated from the soils tests are inputted directly into a regression software program that calculates a soil classification and construction requirements for the in situ soil.

Figure 19. Rapid Soils Analysis Kit field equipment.

Figure 20. The Rapid Soils Analysis Kit packaged in two Pelican cases.

Equipment description

Two key instruments enabled miniaturization of a permanent soil laboratory testing facility to a mobile field laboratory, a 700-watt microwave oven (Figure 21), and a set of small-diameter sieves and accompanying sieve shaker (8 in. × 8 in. × 16 in.) (Figures 22–23). The 3-in.-diam by 1-in.-tall sieves are the smallest ASTM sieves commonly manufactured that still provide laboratory quality results. Commercial, off-the-shelf components are essential in the JRAC program to allow replacements to be readily acquired worldwide. The permanent counterparts of these instruments are typically a large oven and a large sieve tower and shaker, both of which are heavy, cumbersome, and logistically impossible to transport with a small, deployable, site assessment vehicle or as a two-man carry.

Figure 21. 700-watt microwave oven and coffee grinder.

Figure 22. 3-in.-diam ASTM sieves.

Figure 23. Shaker for 3-in.-diam sieves.

Typical tools used to sample and process soils in a laboratory setting are already small enough to be portable and robust enough for field use (Figure 24).

Figure 24. Tools for sampling and processing field soil specimens.

The provided tools are designed to be used in a step-wise fashion to minimize the error on the user in a 22-step procedure outlined in Appendix E.

The microwave is first employed to dry out the field sample for sieving. The mortar and pestle, grinder, and large No. 40 sieve allow processing of the soil into its natural gradation. The splitter subdivides the soil into a representative sample. The sieves and sieve shaker then separate out the required size fractions to determine the grain size distribution. Lastly, the plastic limit device and/or glass plate is used to determine the plastic limit of the soil to complete the USCS classification. Following is a discussion of the particular uses of each principal component of the RSAK to best achieve a contingency classification of the soil.

Microwave oven

The microwave drying process is a critical step in the soil analysis as it provides a technique to rapidly dry the soil to enable pulverization for sieving. This is an essential step in obtaining a GSD for use in the USCS soil classification. Determination of the in situ moisture content also sets the construction logistics for time, manpower, and effort required to meet

design specifications. A sample between 200 and 300 g is placed in the microwave and dried at full power in 1-min intervals until a change in weight of less than 1% percent between the initial and final occurs, at which point the soil has been dried similarly to the oven-drying technique. This represents the ideal technique for rapidly estimating the moisture-density response of the soil in the field.

Mortar and pestle/coffee grinder

After microwave drying of soils containing a fine-grained fraction, "clods" of soil will be present as a result of rapidly driving out moisture from wet clumps of soil. Left alone, these clods would skew the grain size curve to the coarse side and create a false classification of the soil, which in turn would lead to improper construction guidance. Traditional tools to process soils are the mortal and pestle (Figure 24), which can be used to grind down hard clods into much finer material. The mortar and pestle also allows separation of true aggregate from soil clods by observing their response to grinding. Once a coarse separation of the soil has occurred and any aggregate has been removed, there will still remain a large number of very fine clods that cannot be ground any finer with the mortar and pestle. To reduce these fine clods to a powdered material that can pass the No. 200 sieve during dry sieving, the RSAK introduces a coffee grinder that can pulverize these fine clods into powder (Figure 21). As shown in the classification section of the report, the coffee grinder makes classification of fat and lean clays much more feasible, whereas mortar and pestle refinement typically results in a sandy-clay designation.

Splitter

Once the field soil has been dried and pulverized, a representative sample is required of the processed soil prior to sieving. To achieve this blending, a stainless steel, 0.5-in.-diam splitter (Figure 25) is provided to split out representative samples of field soil taken from either a single site or multiple sites. The splitter also acts as an additional 12-mm (0.5-in.) size sieve that screens out larger aggregate that otherwise would not fit in the RSAK's 1-in.-tall sieves. Because the mass of larger aggregate can have a significant influence on the dry density of a soil (Torrey and Donaghe 1991), it is important to include the capability of measuring the percentage of large aggregate in a field setting. To adjust the grain size to account for any coarse material retained on the splitter, the mass of
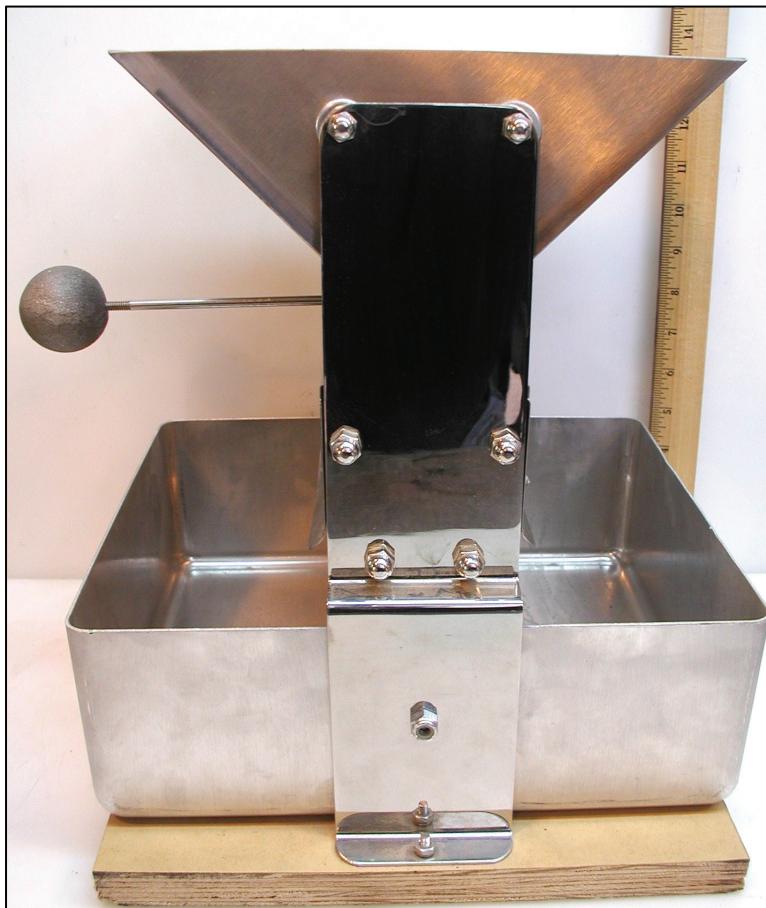
Figure 25. 0.5-in.-diam soil splitter.

material retained on the splitter is recorded and divided by the total mass of the dried soil sample, which is the percent retained on the splitter in Equation 6.1. Since only half of the dried soil is actually passed through the finer sieves according to the steps outlined in Appendix E, the amount of 0.5 in.-plus material that would have been retained for the smaller sample is M_{sp} calculated in Equation 6.1, which is the percent retained on the splitter multiplied by the cumulative weight retained on individual sieves, M_f.

$$M_{sp} = M_f \times \left[\frac{\% \ retained \ on \ splitter \ / \ 100}{1 - (\% \ retained \ on \ splitter \ ) \ / \ 100} \right] \qquad (6.1)$$

Once M_{sp} is known, the percent passing each sieve becomes the cumulative mass passing each sieve divided by the new total mass of soil, $M_{sp} + M_f$. This adjusts the grain size by making the smaller soil particles a smaller percentage of the overall grain size distribution, thereby weighting the curve to the coarser particle size.

Sieves and sieve shaker

To provide a means of obtaining a grain size distribution comparable to a laboratory soil investigation, a series of 3-in.-diam ASTM standard soil sieves is included, along with a shaker. To evaluate the capability of these sieves for an ASTM standard soil classification, a series of experiments was conducted to determine the optimum duration and sample size to provide a good estimate of the classification properties. Several GSD curves were obtained from drying, splitting, and sieving three particular soils: SM coarse, SP-SC, and SP (see Appendix A). These investigations revealed that a logarithmic sieve distribution of a factor of 2 provided a very good estimate to the large sieve soil classification and predicted the correct USCS designation. Based on those initial soil tests, the following are the recommended sieve sizes included in the stack: 9.5 mm (3/8 in.), 4.75 mm (No. 4), 2 mm (No. 10), 0.85 mm (No. 20), 0.425 mm (No. 40), 0.15 mm (No. 100), 0.075 mm (No. 200), and the pan.

ASTM C136 specifies that no more than 0.7 g/cm^2 be retained on any individual sieve. For a 3-in. sieve, this limits the mass to 32 g. An overloaded sieve with a mass of soil exceeding this limit is ineffective in allowing finer material to pass. To avoid the overloading of sieves, it is suggested that no more than 75 g of dry soil be passed through the sieve stack, and less in cases where poorly graded soils exist. The sampling procedure requires that a field specimen be placed through the sieves in two equal portions. This limits the maximum dry field sample to less than 150 g. The moist field sample collected should not exceed 300 g, and therefore should be less than 300 g when dried. The splitter controls the sieved sample size by splitting the 300 g dry field sample into two 150-g or less size samples to meet the specified weight requirements.

To determine a sufficient shake time using the small electric shaker, a gap-graded silty-sand (Appendix A: SM coarse) soil was selected for classification. Approximately 60 g of an oven-dried sample was placed in the sieve stack and shaken. After each minute of shake time, the sieves were carefully removed, weighed, and restacked. This was repeated each minute for 7 min, and the results are presented in Figure 26. This figure shows that after 4 min of sieving, the percent reduction in mass between sieves is less than 2% with little change at each subsequent minute. A sieve analysis after 4 min represents a good estimate of the grain size properties due to the accuracy of the process, the sensitivity of the measuring balance, and the expedient nature of the test. Therefore, in the interest of time, a shake

time of 4 min was found suitable to achieving a good approximation of the laboratory grain size. For reference, ASTM C136 states that the test should be concluded only after a maximum of 1% change in mass occurs. Figure 26 shows that this will occur no earlier than 7 min of sieving, nearly double the time at which 2% change occurs. An expedient soil classification requires two split samples to be sieved, which means that any increase in time for shaking the sample doubles the field time to complete the test by double that amount. In order to provide a means to classify the soil in under 1 hr, the improved accuracy afforded by this extended time frame was deemed not significant.
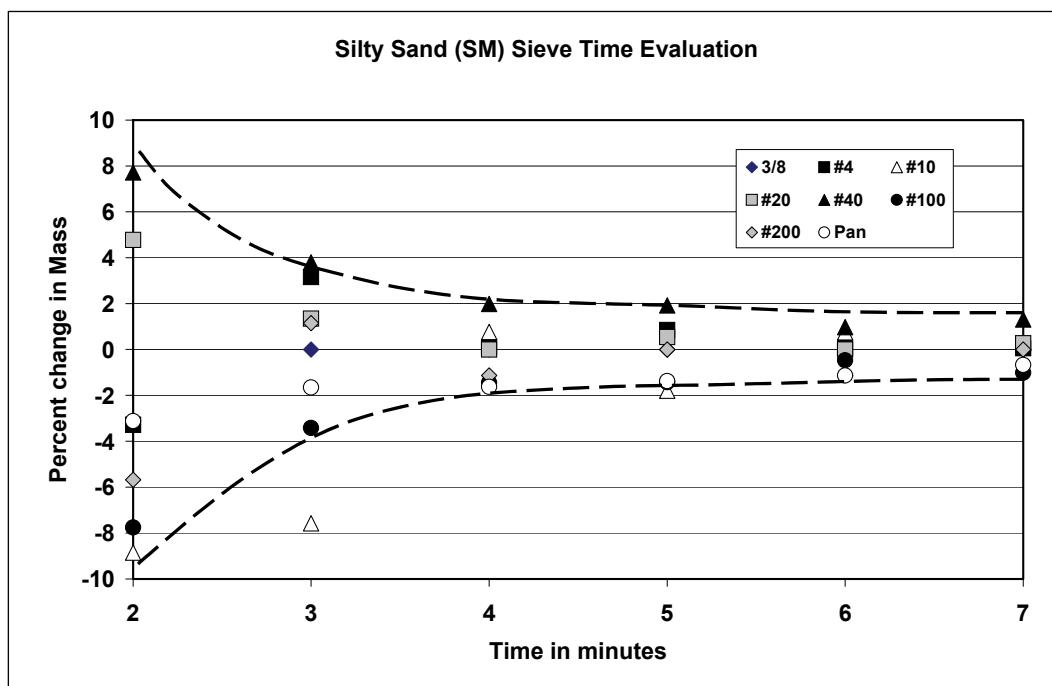
Figure 26. Analysis of sieve time vs. change in mass with each sieve.

Balance

To enable soil mass to be measured, an 800-g balance is included in the suite with an accuracy of ±0.01 g. ASTM D4318 dictates this level of accuracy for measuring the PL. The 800-g balance limits the analysis of large field samples but provides sufficient capacity for a typical 300-g moist soil specimen and accompanying 150-g bowl used in RSAK.

Plastic limit

The most difficult test to conduct in the field instrumentation suite is the PL test. Traditionally, this test involves hand rolling of wetted soil into

threads 1/8-in. in diameter repeatedly until cracks begin to show in the completed thread. Laboratory and field experience is necessary to enable the soldier to conduct this test properly. A Plexiglas board is provided in the toolkit to allow hand rolling of threads when desired. To assist the inexperienced tester, a plastic limit tool is provided which is a Plexiglas box containing a base guide, sliding lid, and adhesive paper strips that are placed on the base and lid to provide friction and soil drying during rolling of soil threads (Figure 24). The plastic limit tool allows the user to place small balls (2 g or less) of wetted soil on the base and then use the base guide and sliding lid to roll the soil into a thread. The base guide has a ridge located at 1/8-in. height that prevents the sliding lid from rolling threads any finer, indicating completion of the test. ASTM D4318 allows the use of the plastic limit tool in determining the PL for the soil.

Soil preparation for the PL test is obtained in a nonstandard fashion. From the dried, pulverized soil passed through the sieve stacks, soil passing the No. 40 sieve is collected and stored for use. The collected soil must then be rewetted in a bowl to a moisture content exceeding that of the expected PL and then redried during thread rolling. ASTM D4318 recommends that oven-dried soil not be used for this test, as oven-dried soil can potentially alter the PL especially in clayey soils (Basma et al. 1994). If so desired, a large, No. 40 sieve is included in the toolkit from which samples of in situ soil can be screened at their natural water content to create a sample to conduct the PL. However, unless ample time is available to the soldier, the need for estimated properties in a very short time necessitates the use of microwave-dried soil.

Deviations from ASTM

The rapid soil analysis procedure limits the precision with which traditional laboratory tests can be executed. Below is a listing of the typical requirements for conduct of a given soils test compared to that which is performed in the RSAK.

Microwave drying

Drying time is followed more conservatively than ASTM D4643 by sampling the soil after every minute of drying to prevent overheating of granular materials and allow testing of smaller sample sizes such as the PL. ASTM recommends an initial 3-min drying time followed by 1-min increments. The included RSAK software allows an on-screen visualization

of the change in moisture with time to assist the operator in minimizing the potential for overdrying (which can overpredict the moisture content in fine-grained soils).

Sample size is compromised. ASTM recommends 500 g or more for obtaining moisture content in soils with particles larger than the No. 4 sieve. The RSAK has procedural limitations that do not allow the use of greater than 300 g to complete the sieve analysis. ASTM recommends a minimum 100-g sample for any microwave drying sample, which is much greater than the 10 to 20 g of moist material than can reasonably be rolled into threads during the PL test in a 1-hr time frame.

According to ASTM, microwave drying is considered complete when incremental weight differences are no greater than 0.1% of the total wet mass of the sample. This RSAK procedure has an equivalent check; however, this can be too restrictive for the small sample sizes used in the PL, in which case user judgment on when to stop the test is required.

Sieving

No wash sieve is conducted in the RSAK because of the limitations on time and resources in the field. Only the dry sieve is conducted, which ultimately limits the accuracy of No. 200 soil fraction. In the "Comparison to laboratory results" section, it is noted that, in all cohesive soil cases, the RSAK predicts a lower fine content as a direct result of not moistening the soil as per ASTM C117. ASTM C117 states that only when the accuracy of material passing the No. 200 sieve is required should wash sieving be used. The use of the coffee grinder is an attempt to mitigate this discrepancy, providing a means to generate sufficient fines quantity to differentiate fine-grained soils from coarse-grained soils.

ASTM recommends sieving until no more than 1% change occurs in 1 min of sieve time. According to Figure 26, this would typically occur at about 7 min of sieve time. Considering that two cycles of sieving are required through the small sieves, at least 14 min plus downtime would be required to complete the analysis. The RSAK reduces the sieve time by half. Note that only a 2% change in mass occurs after 4 min, which is considered acceptable for contingency analysis.

The RSAK uses a reduced representative sample size of no more than 300 g prior to splitting and no more than 150 g for sieving after splitting.

ASTM recommends 1000 g for 3/8-in. size material after splitting and 300 g for minus No. 4 fraction. This reduces the accuracy for classification of coarse-grained soils, but the logistics of field evaluation limit large sample sizes.

ASTM requires retesting of the sieve analysis if greater than 0.3% of the initial dry weight is lost during the process. Since the RSAK uses reduced sample sizes, this produces too tight a restriction on the mass measurement. Care of the soil in an outdoor environment along with balance error in windy conditions requires a leniency in the RSAK allowable tolerance, which is set at 2%.

ASTM states that no more than 7 kg/m² can be retained on an individual sieve in order to allow free passage of finer material. The RSAK uses this same requirement, although the smaller sieve diameters dictate a much smaller weight fraction. This requires smaller initial sample sizes when poorly graded soils are being tested.

Atterberg limits

One significant deviation from ASTM is the use of microwave-dried soil prior to conducting the PL test. The test is conducted by taking the dried soil and rewetting it to just beyond the PL prior to rolling threads. ASTM requires wetting of air-dried, not oven-dried, soil to beyond its LL, allowing the soil to sit for a period of 16 to 24 hr and then to steadily dry to the PL. Experience with the RSAK has shown that soils respond well enough to the wetting technique to provide reasonable estimates of PL for contingency construction specifications.

Given the small sample sizes used for the PL, the balance has a maximum weight of only 800 g, whereas ASTM requires at least 1 kg or greater. However, care was taken to select an electronic balance with an accuracy of 0.01 g (as per ASTM) to minimize compounded errors in determining the PL.

Another significant deviation is the avoidance of conducting the LL test in the interest of time. Instead, a regression equation using the input of PL and the texture of the fines material estimates a LL to allow classification of the soil. Significant errors can occur in the magnitude of the LL. However, this value is not used in determining any construction parameters, but only to distinguish between clays and silts. Error may

occur in distinguishing between fat clays and lean clays if the PL is low for fat clay. This is considered an exception, and materials this poor should require further investigation for contingency construction.

Comparison to laboratory results

To evaluate the RSAK's capability to capture the physical properties of typical field soils, validation tests were carried out in the laboratory. A laboratory comparison was conducted on a total of seven soils of known laboratory values. Five samples were of varying plasticity: a fat clay (CH), a lean clay (CL), a silty-clay (CL-ML), a sandy-clay gravel (SP-SC), and a coarse silty sand (SM). The two additional samples were nonplastic, consisting of a fine silty-sand (SM) and an ASTM C33 concrete sand (SP). Each soil sample was air-dried, microwave-dried, and sieved using the RSAK, and then a PL test was conducted on material passing the No. 40 sieve as per ASTM. Data were collected, and the resulting comparative tables and graphs verify the accuracy of plasticity, gradation, and classification as compared with a full-scale laboratory. Comparisons were also made of the predictive capability of the RSAK through an analysis of moisture-density and unsoaked CBR curves at varying compaction energies (Table 8 and Appendix B). The 2007 JRAC Demonstration report (Anderton et al. 2008) details the deployment of the soil classification kit in the field on the RAVEN and its ability to predict the in situ conditions.

The following lists the complete set of analysis values obtained and predicted in this validation study:

- Grain size distribution (GSD) – measured
- Plastic limit – measured
- Liquid limit – predicted
- Soil classification – measured
- Optimum moisture content – predicted for standard (CE12) and modified (CE55) energy Levels
    - G1 analysis using WES Database
    - G2 analysis using Overseas Database
- Maximum dry density – predicted for standard (CE12) and modified (CE55) energy Levels
    - G1 analysis using WES Database
    - G2 analysis using Overseas Database
- Complete moisture-density curve – predicted

- Unsoaked California bearing ratio curve – predicted for standard (CE12) and modified (CE55) energy levels
  - o G1 analysis using soil specific single variate regression
  - o G2 analysis using general nonlinear multivariate regression algorithm

Several means exist to compare the RSAK results to the laboratory values. The following describes the maximum predictive capability of the RSAK by taking a soil with no known properties and computing a finalized moisture-density and CBR curve. This is to demonstrate the ability to provide field construction guidance in the absence of any available information. Clearly, improvements to the predictive results shown can be made if properties such as grain size distribution and Atterberg limits are known beforehand. However, this is an unlikely condition in a JRAC contingency scenario where, at best, only a general soil classification for an area of interest is known.

Grain size distribution

A series of seven soils were selected to test the ability of the RSAK to sufficiently reproduce the GSD of a laboratory-tested specimen. Based on the test protocol for conducting an expedient field sieve analysis (defined in Chapters 4 and 5), a representative sample of approximately 200 to 300 g was obtained, dried in the microwave, and split over the 0.5-in.-diam splitter. The sieve analysis was conducted and compared to results obtained by the ERDC Geotechnical Laboratory's technicians on similar representative samples. Appendix A shows the comparative grain size distribution plots between the laboratory and the RSAK.

The following are general trends on the grain size performance of the RSAK:

1. For all the soils, a lower fine content (minus No. 200 fraction) was measured than was derived from the laboratory wash sieve analysis. This is to be expected and is a direct result of the preliminary microwave drying of the soil prior to sieving. Microwave drying results in fines adhering to larger aggregate and not being passed on to the finer sieves. Further, physical breakdown of the soil by mortar/pestle/grinder techniques still does not pulverize hardened soil clods as well as soaking soil clods in water.

2. In all cases, the proper soil classification was generated. Even though the fines content was limited, a sufficient amount of material was retained in the respective sieves to adequately approximate the true grain size curve. Program calculation of the coefficients of uniformity and curvature based on $D10$, $D30$, and $D60$ diameters produced the proper well and poorly graded properties of the soil.

3. The RSAK does well in approximating the shape of gap-graded soils (SM, SP-SC).

4. The RSAK is most effective both in time and accuracy at grain size prediction for coarse-grained soils with limited fines content.

Plasticity

Little variability was noted between laboratory PL tests and RSAK plastic limit tests. A strict ASTM-conducted PL test was performed by the ERDC Geotechnical Laboratory on moist soils and compared to similar soil that had previously been oven-dried. For the fine-grained soils tested, plastic limits were obtained within about ±1% of the true laboratory value (Table 7). Variability is anticipated for lateritic soils, whose plasticity character changes dramatically with oven drying. At present, there is no protocol to address this type of soil within the RSAK.

Table 7. Comparison of Atterberg limits between ERDC laboratory and the RSAK.

Soil Name:	Fat Clay			Lean Clay			Silty Clay			Sandy Clay			Silty Sand (C)		
USCS:	**CH**			**CL**			**CL-ML**			**SP-SC**			**SM**		
	Lab	*G1*	*G2*	*Lab*	*G1*	*G2*	*Lab*	*G1*	*G2*	*Lab*	*G1*	*G2*	*Lab*	*G1*	*G2*
Plastic Limit	22	25	25	21	21	21	23	23	23	10.5	11	11	18	18	18
Liquid Limit	68	59	54	37	44	42	28	51	29	30	14	23	22	33	22
Plasticity Index	46	34	29	16	23	21	5	28	6	19.5	3	12	4	15	4

It can be seen that the textural refinements made in the G2 analysis greatly improve the LL predictions over the G1 analysis, resulting in an improved soil classification.

OMC-MDD/Proctor curves

For each of the seven soils presented, a comparison was made between actual laboratory Proctor tests and values predicted from both analyses, G1 and G2. Table 8 presents a summary of the average predicted values for the maximum dry density and optimum moisture content, compared with their values determined in the laboratory. Detailed plots of the entire

predicted Proctor curves are shown in Appendix B. Proctor tests were conducted at two energies, modified (CE-55) and standard (CE-12), as defined previously. To illustrate the variability associated with the predicted Proctor results, in the plots shown in Appendix B, a statistical window is drawn that bounds a one standard deviation for both predicted OMC and MDD (as summarized in Table 8). For most of the plots, the actual OMC and MDD falls within this window suggesting that the curve fit is reliable for contingency construction. Points of MDD and OMC that are beyond one standard deviation are highlighted in bold print in Table 8.

Shown in each plot is the estimated range of MDD for CE-55 energy taken from Army FM 5-410, which is the present state-of-the-practice guide for military field construction values. The large, non-specific range listed certainly encompasses the measured OMC and MDD, but fails to narrow this range to a reasonable error. Thus, selection of a median value would be the likely best answer to a design scenario, but the RSAK provides a more refined answer with a much smaller design window. Further, FM 5-410 does not give any guidance as to design water content, critical to mission success. The RSAK does provide this value and proves to be a very reliable estimate of OMC for any energy level.

Table 8. Summary of predicted vs. measured MDD and OMC values.[a]

Modified Proctor Energy						
	Predicted MDD			Predicted OMC		
Soil Type	High	Low	Lab[b]	High	Low	Lab[b]
CH	116.6	103.0	*111.3*	20.0	14.1	*15.5*
CL	120.4	106.8	*116.8*	18.7	12.7	*13.1*
SP-SC	146.9	133.3	*135.7*	6.7	0.8	*5.4*
CL-ML	119.6	106.0	*116.2*	17.4	11.4	*12.9*
SM Coarse	135.2	121.6	***138.0***	12.0	6.1	***5.2***
SM Fine	122.8	109.3	*121.3*	12.5	8.6	***7.4***
SP	128.2	114.7	***114.1***	9.9	5.9	*6.0*
Standard Proctor Energy						
	Predicted MDD			Predicted OMC		
Soil Type	High	Low	Lab[b]	High	Low	Lab[b]
CH	109.5	95.9	*97.1*	22.2	16.3	*21.8*
CL	113.3	99.7	*110.0*	20.9	15.0	*15.2*
SP-SC	139.8	126.3	*130.1*	9.0	3.1	*5.6*
CL-ML	113.3	99.7	*107.2*	18.9	12.9	*16.5*
SM Coarse	128.1	114.5	***135.0***	14.3	8.4	***7.0***
SM Fine	119.1	105.6	*118.1*	14.0	10.0	***8.8***
SP	124.4	110.9	*111.0*	11.3	7.3	*8.0*

[a] High/low values are based on ±1 standard deviation from the predicted mean.

[b] Lab values highlighted in bold font represent values outside the predicted bounds.

CBR values

For each of the seven soils presented, a comparison was made between actual laboratory unsoaked CBR tests and values predicted from both analyses, G1 and G2, as shown in Appendix C. CBR tests were conducted at two energies, modified (CE-55) and standard (CE-12), as defined previously. Predicted curves for the G2 analysis include both the square root and the logarithmic regressions for comparison. Noted on each plot is the range of CBR provided for in FM 5-410. In most cases, this range provides an overly conservative estimate of CBR for short mission scenario contingency design. These values would be representative of typical long-term minimum strength designs.

7   System Integration

Software

To provide a tool for rapid soil classification, a coupling between the regression model and the field instrumentation suite is required. A software package was developed which prompts the user to input field measurements in a systematic format. After completing data inputs over a sequence of screens, a USCS soil classification is returned. The user can then generate the desired construction plots, the Proctor moisture content-density and CBR-moisture, for one of four combinations: modified or standard Proctor energy and soaked or unsoaked CBR.

This coupling of the two systems provides the desired speed of analyses required to meet the demands of a JRAC scenario. With a properly trained team of field soldiers, a soil can be sampled, tested, and information displayed on screen in 1 hr of field time versus the ≥3-day alternative requiring soil to be taken to a laboratory.

Program design

The soil analysis program, SoilClassification.exe, was written using Visual Basic.Net Version 2003 and can be run effectively on any PC with the appropriate .NET suite of tools installed or containing at least the Windows XP operating system. The program allows the user to interact with the program using a touch screen-enabled computer (i.e., a Panasonic Toughbook). An on-screen numeric and character keyboard were developed to enable the user to do this.

The program was designed as a wizard to provide step-by-step instructions on determining the soil classification of one or more samples. The actual code for the program was compiled as a dynamic link library to allow the program to be hosted within other programs. Currently, it is hosted in the JRAC software tools suite.

For computer systems with later operating systems or those that do not have access to the .NET tools, the results can also be obtained through use of a Microsoft EXCEL spreadsheet that originally served as the basis for the SoilClassification.exe program. The advantage of the two systems is

that the .NET version can be run on a laptop computer attached to a mobile field vehicle whereas the EXCEL version can be imported into a Pocket PC or other mobile computing device that can allow the user even greater freedom in the field.

Program process

The RSAK software, SoilClassification.exe, directs the user in a step-wise fashion as to what step must be run next or data collected. Its design is fairly rigid in that a task must be completed in a certain order before continuing on. This is to ensure that the software can be picked up and successfully operated by users with only the briefest training, a scenario typical in a contingency military environment.

Appendix D provides a visual user manual that describes, screen by screen, the operation of SoilClassification.exe. The following discussion provides an overview of the general functionality of the program, along with comments on the science behind its decision-making process.

Steps 1-12: Describing/reviewing a test sample

When the user first activates the software, he/she is presented the option to either view the results of a previous test or to begin a new test. To begin a new test, the operator is required to define a test sample by site location, date of test, and description of test item. Further data that are requested, if available, include the time and latitude/longitude, which can be used to establish a map-based reference for later analysis. If the user wants to view an existing test, he searches based on site location, date of test, and test description. For instance, if data were recorded only for the in situ moisture content, the user will see that only those test data are available. If soil classification data were recorded, then all three stored items (moisture content, USCS classification, and the construction curves) will be available to the user.

Steps 13-19: Initial soil drying

To begin the soils analysis, a moist field sample of between 200 and 300 g must be obtained. This limitation on size helps the user arrive at the maximum 150-g dried, split sample at the completion of the processing. The soil sample can be from a single location or can be a mixed sample from discrete points in an area of interest. Before any sieve work can be

conducted, the soil must be completely dried in the microwave. The software prompts the user to dry the soil in 1-min increments until completely dry. This first series of screens prompts the user for the required information to compute the initial moisture content of the field sample.

Steps 20-21: Beginning a soil classification

At the end of the moisture content test, the user can end the program if that is the only desired piece of information, such as a moisture check during field construction or a check of available moisture in a borrow area. However, if the user wishes to determine the soil classification and construction properties, he continues to the next series of screens.

Steps 22-26: Crushing and splitting a sample

To begin soil processing, the dried sample from the previous step is pulverized with a mortar and pestle and coffee grinder with care taken not to break up soft aggregate, but only soil clods that have formed during microwave drying. Determining what is an aggregate and what is a soil clod will require judgment from the user, as no guidance is provided in the software. The wire sieve brush can be used to scrape off fines adhered to larger aggregate to improve the determination of the fine fraction. This is the most complicated and involved portion of the soils analysis, typically requiring the greatest amount of time to complete.

During the drying and crushing of the soil, different aggregate size fractions naturally segregate out to aid in the processing, being stored in more than one container or bowl (i.e., gravels and sands in one bowl, fine powdered silt and clay in another). Once the soil has been reduced to its natural grain size, it is poured into the splitter to reconstitute the divided soil fractions to create a pair of representative and uniform soil samples, each of which is of sufficient size for soil sieving. This weight of aggregate retained on the splitter box is recorded for use in normalizing the GSD to account for larger size particles.

Steps 27-33: Sieving the soil

The most complicated part of the soil analysis is followed by the easiest part in the classification process, the physical sieving of the soil. The software prompts the user to weigh out the series of sieves (empty), which is

done only once for each analysis. It is recommended not to assign a permanent weight to each sieve by inscribing the frame because, with time, sieve weights can change as the result of lodged soil grains or damage. The user then pours approximately half of the soil contained in only one pan of the splitter into a bowl to get an initial weight of sample and then pours that into the sieve stack. The sieve stack is shaken for 4 min using an included egg timer, the sieves are removed, and each is weighed full.

The program provides a series of error checks at this point. First, it asks the user if the weights are correct, to ensure that no sieve has been missed. The program then checks to see if the weight on each sieve is at least the weight of the sieve empty. This error can arise due to outside wind causing balance fluctuations in the hundredths of a gram range. The program simply inputs the empty sieve weight if a lower number was entered. The program then checks to see if more than 32 g is retained on any one sieve, which would violate ASTM criteria. The user has the option of continuing if so desired. Next, the program checks to see if more than 2% of the total weight was lost during sieving, indicating an improper data entry, spillage of material during handling, or slight error in balance readings due to wind (typical). The program displays the actual percent loss, and the operator has the option either to accept the loss value and continue or to abort the test. If the user continues, he repeats the sieving process with the remainder of the soil in the pan. If the user aborts, all sieve data are discarded and the program restarts at Step 27, requiring the user to begin the sieving process again using the other half of the split sample contained in the second pan in the splitter.

If the user aborts this last soil sample, meaning he has failed the soil tested in the first pan from the splitter and then failed the soil in the second pan from the splitter, the original soil sample has been exhausted. The program sends the user back to Step 13, requiring him to obtain a new field sample and begin the drying/crushing/splitting/sieving process once again.

Steps 34-40: Plastic limit test

Once sieving is complete, any material that passes the No. 40 sieve is to be collected and wetted to perform the PL test as per ASTM D4318. If the user is unable to roll threads of 1/8-in. diameter prior to cracking, the soil is considered nonplastic, the user answers no to the thread roll question,

and the computer assigns a value of zero to the PL and subsequently a value of zero to the plasticity index for computational purposes.

If the user can roll threads and plasticity is evident in the soil, then the moisture content routine as described in Step 13 begins again. It is recommended that 10 g of moistened threads be collected for testing. At this small sample weight, the microwave will quickly dry the soil out, and the threat of overdrying is present. Therefore, the operator should watch the relative moisture change percentage window in the software to see when a value of 1% or less change is nearly reached and then adjust subsequent drying times to prevent severe overdrying of the soil.

Once the soil is dried, the user is asked to identify the texture of the fine soil fraction, whether clayey or silty in consistency—a question that can be answered by using the expedient field classification techniques given in FM 5-410.

Steps 41-44: Data analysis

Once the user has completed the soil analysis, the regression algorithms begin. First, the program estimates a LL and then a plasticity index for the soil based on the textural classification and the known moisture content recorded. Then, the soil diameters occurring at 10%, 30%, and 60% by weight ($D10$, $D30$, and $D60$, respectively) are estimated via interpolation from the inputted grain size data to compute the coefficients C_c and C_u to determine whether the coarse-grained material is poorly or well graded. Once the weight fractions of sand, gravel, and fines are known, and after C_c, C_u, LL, and PI are calculated, a computerized version of the soil classification flowchart given in ASTM D2487 is followed to provide the user a letter-designated USCS soil classification.

After classifying the soil, the program uses the sieve percentages and PL data to compute the OMC and MDD, and then couples that information with the USCS designation to define a complete Proctor curve. A similar procedure occurs for the CBR value, taking into account the estimated OMC and MDD in addition to the real data collected in the field.

The construction design curves are then displayed as a plotting routine is called. The plotting routine involves a simple graphic user interface run by a series of radio buttons to allow the user to toggle between Proctor, CBR,

and soaked CBR curves at standard or modified energy (Figure 27). The soil plot routine calculates and displays the MDD and the OMC for a desired energy level, standard or modified. Further, the program calculates and displays the desired Proctor curve (standard or modified) and associated CBR plot (soaked or unsoaked). The program further calculates a line at 98% MDD to show the allowable range of moisture content wet and dry of optimum to achieve the specified density or strength requirements. The program also displays the in situ moisture content of the field site.
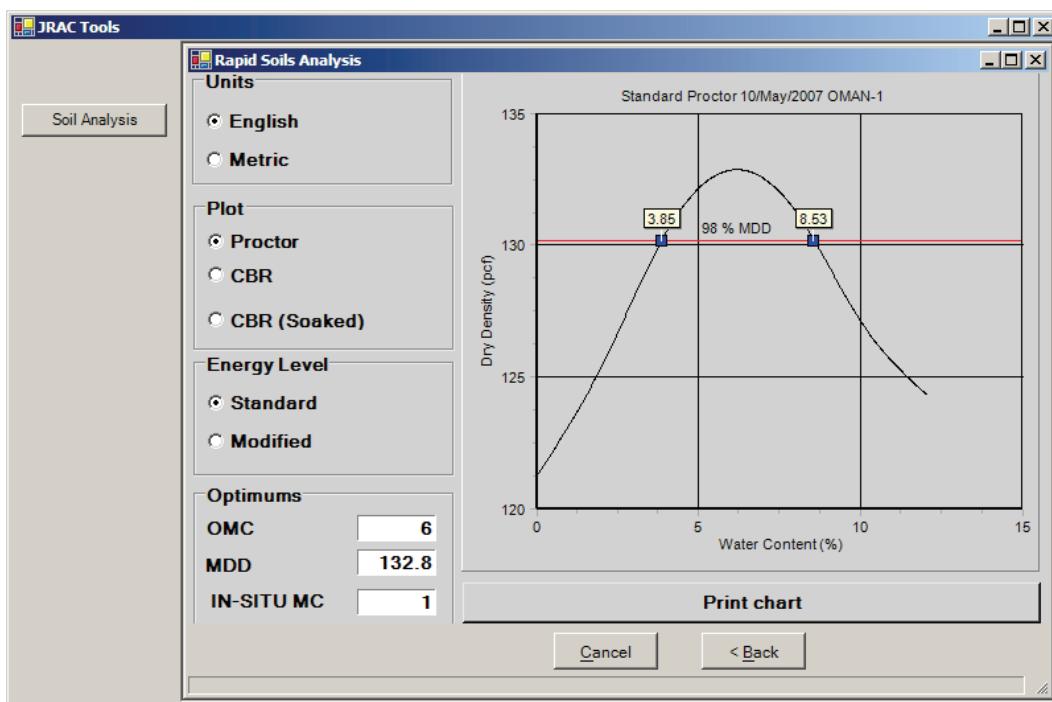
Figure 27. Screenshot of construction design curves from RSAK.

Packaging

The RSAK is delivered to the field in one of two ways. In its initial conception, the RSAK was packaged in defined locations on a utility box designed to fit on the back of a Bobcat Toolcat (Figures 28-30). This vehicle was customized for use in both the 2004 and 2007 JRAC demonstrations and was labeled the RAVEN (Rapid Assessment Vehicle Engineer). This provided a portable platform, along with other key components of site investigation critical to the JRAC mission success, such as a dynamic cone penetrometer and GPS coordinate identification equipment. The RAVEN came equipped with a diesel generator and built-in 110V power strips that power the various tools in the RSAK.

Figure 28. RSAK mounted on the RAVEN prior to 2004 JRAC demonstration.

Figure 29. RSAK in use on the RAVEN during 2004 JRAC demonstration.

Figure 30. RSAK remounted on RAVEN in use during
2007 JRAC demonstration.

Following the 2004 demonstration, military requests for a stand-alone
soils kit arose, and the RSAK was repackaged in a pair of Pelican cases that
enabled the kit to be portable in any vehicle (Figure 31). Each case
(31.5 × 22.9 × 18.9 in.) requires a two-man carry, weighing approximately
75 lb apiece. The only component critical to the portable kit's success is the
availability of a power source to run the microwave, sieve shaker, and
coffee grinder.

Figure 31. RSAK packaged in two large Pelican cases (two-man carry).

Training

Training on the RSAK is nearly as expedient as the soil analysis process itself. Current training involves four distinct sections taking approximately 3 to 4 hr to complete. Figure 32 illustrates a typical soils kit layout and environment during a training session.

1. Introduction (30 min): Break out the RSAK and identify all the components (talk about each component and how it compares to a traditional laboratory test). Show how kit can be repacked.

2. Demonstration (60 min): Take sample soil(s) and demonstrate the use of each kit component, generate data for software inputs, and show the use of the accompanying software.

3. Field sampling (15 min): Participants will obtain a representative sample of soil from the field to perform a soil analysis.

4. Hands-on training (90 min): Small groups take turns analyzing the field sample with the soils tool kit and software in order to obtain a USCS soil classification, Proctor curves, and CBR design curves.

Figure 32. 411th Engineers training on the portable RSAK
(July 2006).

8 Conclusions and Recommendations

Conclusions

The RSAK, developed under the JRAC program, addresses the need for rapid onsite soil characterization, providing both soil classification and construction design parameters in 1 hr. The soils kit includes a small-scale field laboratory consisting of a microwave, electric balance, sieve shaker, sieves, grinder, PL tool, and necessary bowls, spatulas, and scoops. From a small soil sample (~300 g), these tools determine soil moisture content, GSD, and PL. The numerical data generated from these soils tests are input directly into regression software that determines a USCS soil classification. With the soil classification, PL, and GSD, the software uses multiple-linear regressions based upon worldwide soil property databases to estimate optimum water content and maximum dry density for standard (CE-12) and modified (CE-55) Proctor compaction energies. Built-in higher order regression equations compute complete design curves for Proctor density, as-built CBR, and soaked CBR for the constructed condition of the soil of interest. Table 9 summarizes the benefits of the RSAK compared to the current state of practice defined in Army FM 5-410.

Table 9. Comparison of the RSAK to FM 5-410.

Army Field Manual FM 5-410	RSAK
Provides wide band of maximum dry density for modified Proctor CE-55	Provides tighter estimate for maximum dry density for CE-12, CE-55, or equipment-specific energy level
Does not provide optimum moisture content estimation	Provides estimate of OMC for given maximum dry density and energy level
Provides conservative soaked CBR range for design of flexible pavement systems	Provides CBR curves for all given energy levels and delineates between soaked and unsoaked response
Classification based on textural application only	USCS classification based on both textural and laboratory equipment data. Numerical data drive regression analysis
Provides only 13 inorganic USCS soil classifications with respective data	Provides estimates for all 22 inorganic USCS soil classifications
Test can only be effectively conducted by experienced soils technician.	Test can be completed in 1-hr time frame with inexperienced operator
No means to provide moisture content	Use of microwave enables determination of moisture content for both in situ and constructed conditions
No power and minimal equipment to transport	Requires transport of equipment and power to operate

An accurate and expedient means to determine soil classification is essential to establish the soil design criteria for military contingency airfield and lines of communication construction using in situ soil. Under a contingency design and construction scenario, only a few hours are available to accumulate necessary ground truth data. Currently, only subjective field analysis techniques are available, whose results fail to provide tangible numerical data that can be used to establish the necessary construction criteria. Obtaining construction design properties requires a traditional soil laboratory that must be stationed at a rear-operating base, with the complication of transporting collected field samples for analysis, requiring days of testing. The RSAK dramatically reduces the logistics of performing in-theater soils analyses. The RSAK is easily transported as a two-man carry, can be used in forward operations, onsite, with a setup time of only a few minutes, and can provide construction data within 1 hr of sampling of soil.

Recommendations

The following topics provide guidance as to future research that can lead to expanding the compatibility of the RSAK with worldwide soils, improving the predictive accuracy of the regressions, and increasing deployability options of the kit to the Army and Joint Forces construction and expeditionary units.

To expand the range of compatible soils with the RSAK:

- Gather and incorporate moisture-density data on marginal soils such as corals and laterites and plastic silts (MH) to improve the usefulness of the RSAK in tropical regions of the world.
- Seek out new databases on coarse-grained soils (sands and gravel mixtures) to improve existing correlations for base-course and large-aggregate construction soils.

To improve the predictive capability of the RSAK:

- Redesign the existing linear regression techniques to employ a neural network approach to analyzing the RSAK data, improving the correlations of the predicted OMC and MDD by making better connections between similar soil properties.
- Develop a turbidity technique to quickly disseminate between silty and clayey soil fractions to alleviate textural classifications.

- Provide larger tools that will enable better classification of coarse-grained soils such as base-course aggregates and will lead to improved predictions of construction design curves.
- Provide confidence intervals on predicted Proctor and CBR design curves to give the user a visual range of data scatter.

To increase the deployability of the RSAK:

- House the RSAK within a modular container, mountable on a standard military High Mobility Multipurpose Wheeled Vehicle, which will enable the kit to be deployed to the theater without hand-carried Pelican cases.
- Design a more comprehensive software system that can handle large volumes of data for easy sorting and form reporting for military construction logs. This will broaden the applicability of the kit and its software.
- Combine the RSAK with current or new field quality control technologies such as the JRAC Rapid Quality Control/Quality Assurance Kit to create a more robust contingency field evaluation tool.

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Appendix A: Grain Size Distribution Data

Grain Size Distribution (Coarse SM)

Grain Size Distribution (CH)

Grain Size Distribution (Fine SM)

Grain Size Distribution (CL)

Grain Size Distribution (SP-SC)

Percent Finer by Weight vs. Grain Size (millimeters)

Legend:
- Laboratory
- Field Kit

Grain Size Distribution (CL-ML)

Percent Finer by Weight vs. Grain Size (millimeters)

Legend:
- Laboratory
- Field Kit

Grain Size Distribution (SP)
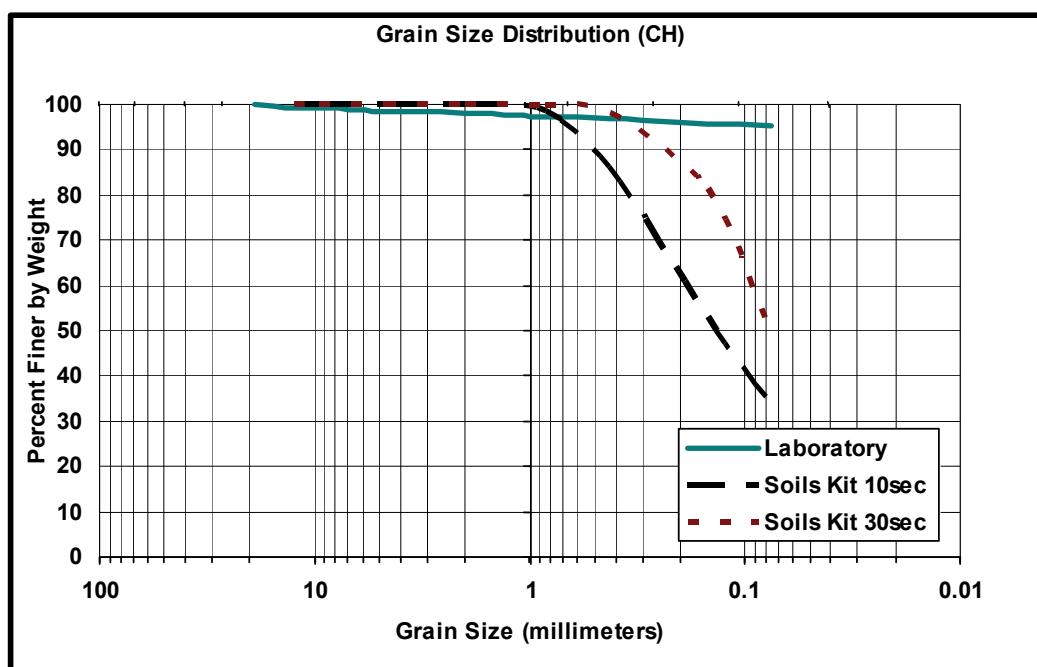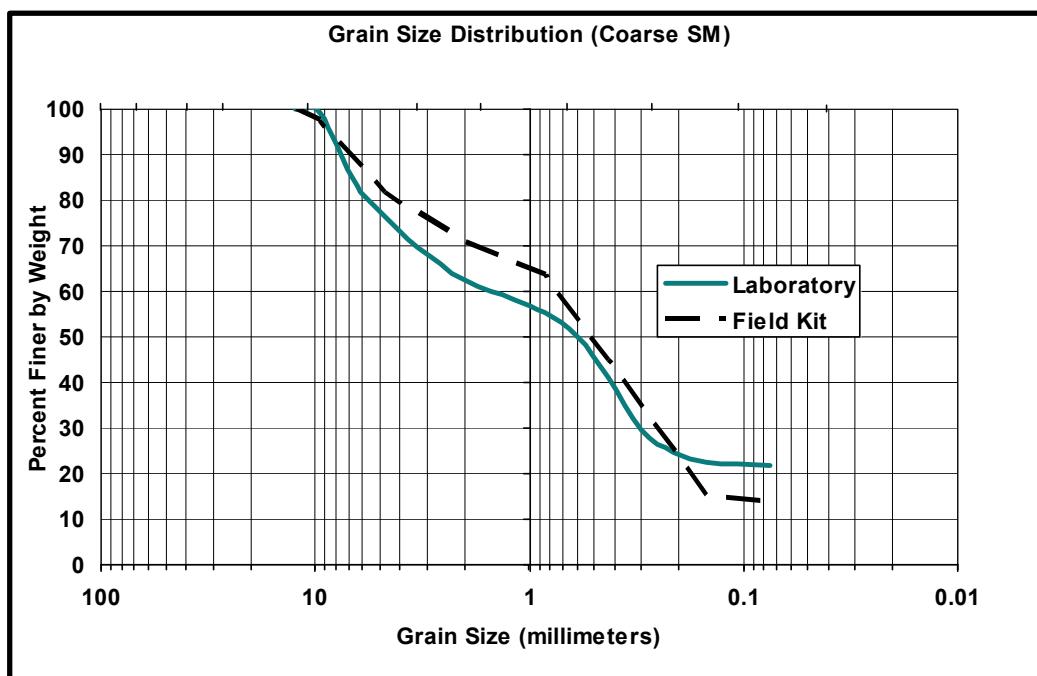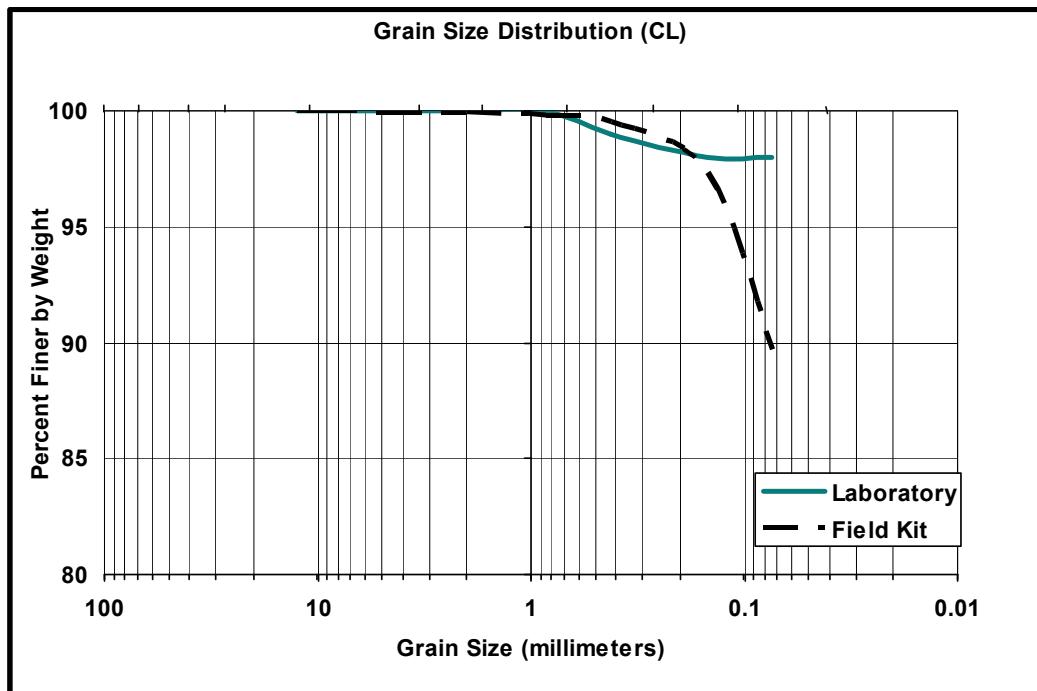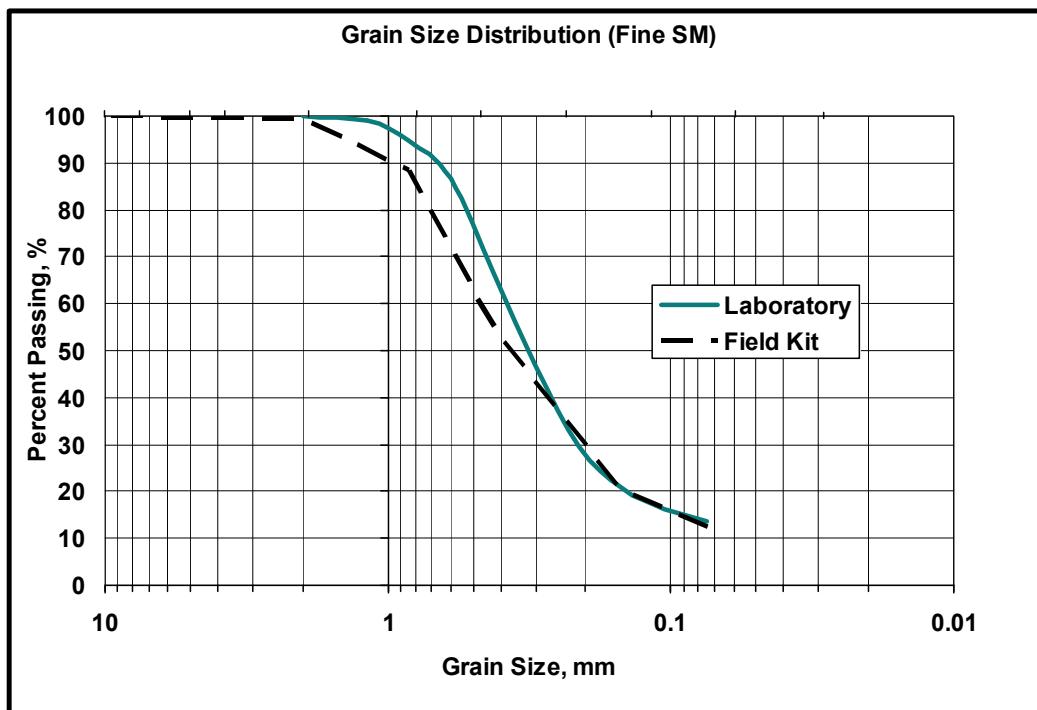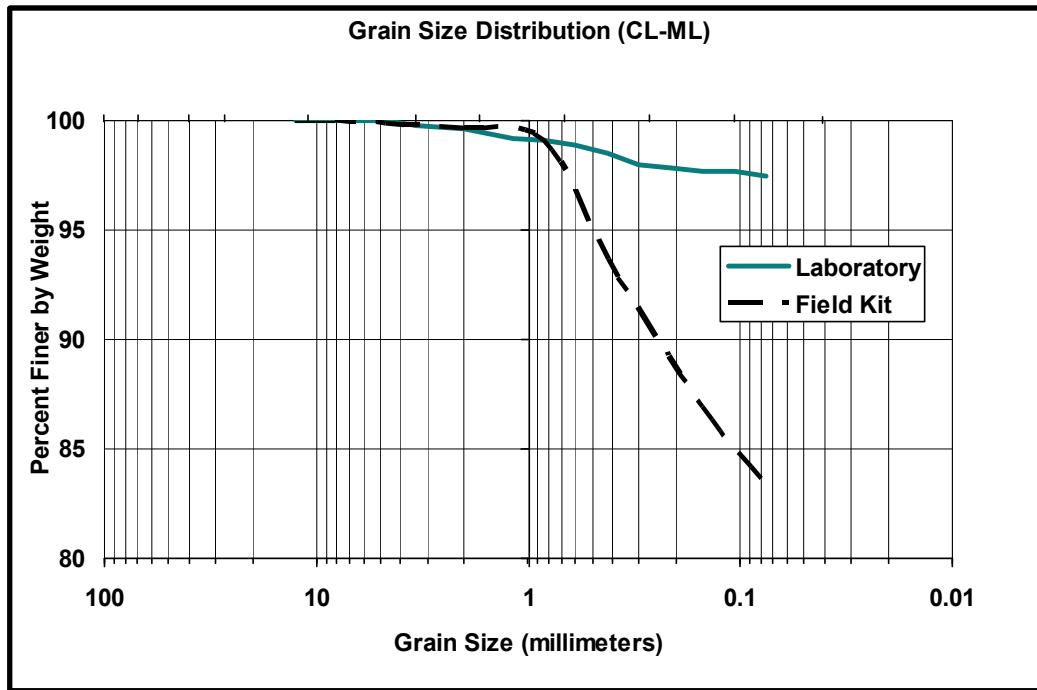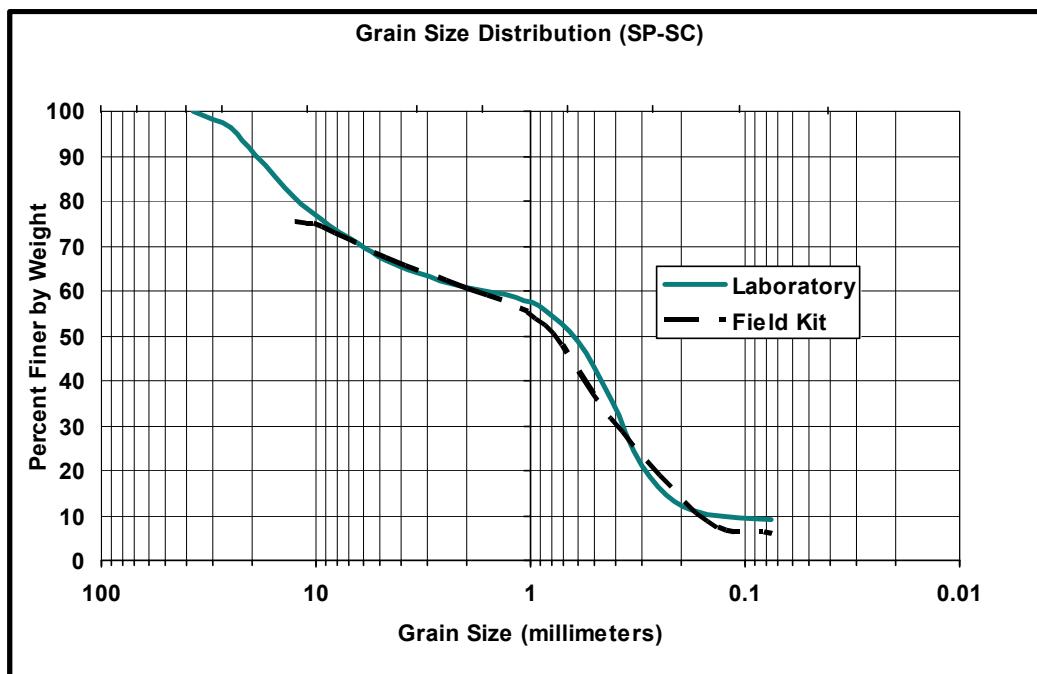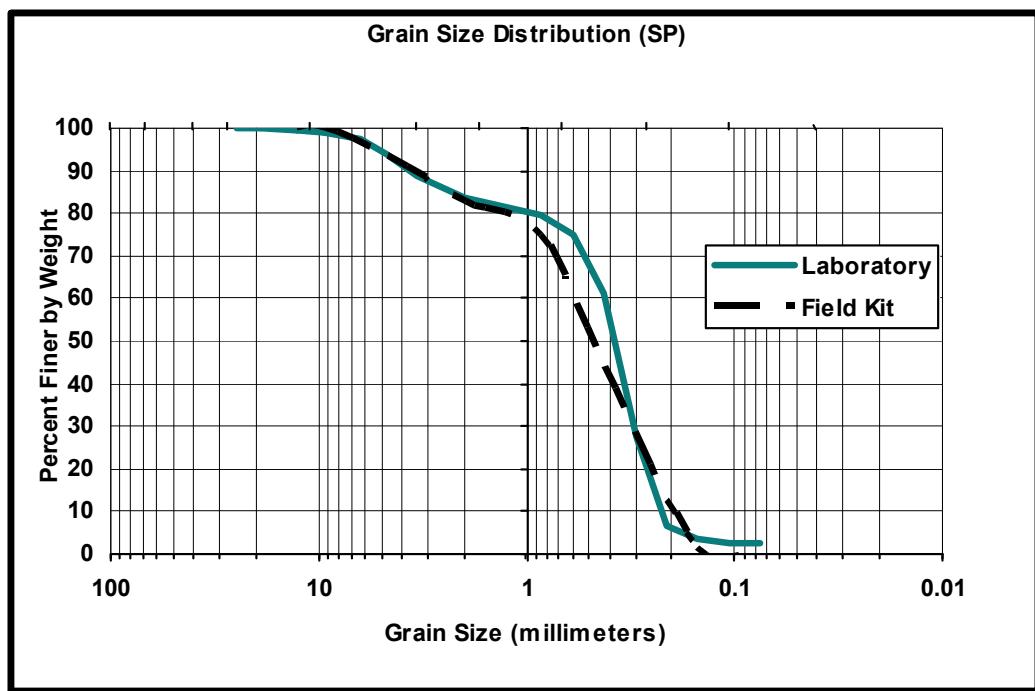
Appendix B: Proctor Compaction Data

Fat Clay: Modified and Standard Proctor Compaction Curves with G1 and G2 Correlations

Lean Clay: Modified and Standard Proctor Compaction Curves with G1 and G2 Correlations
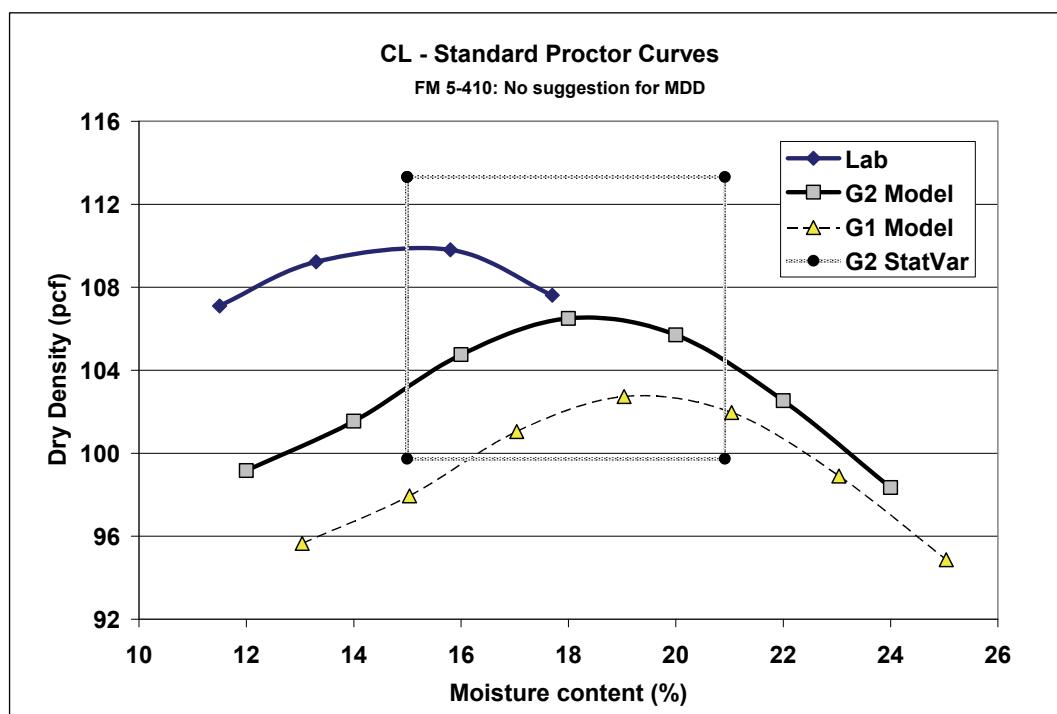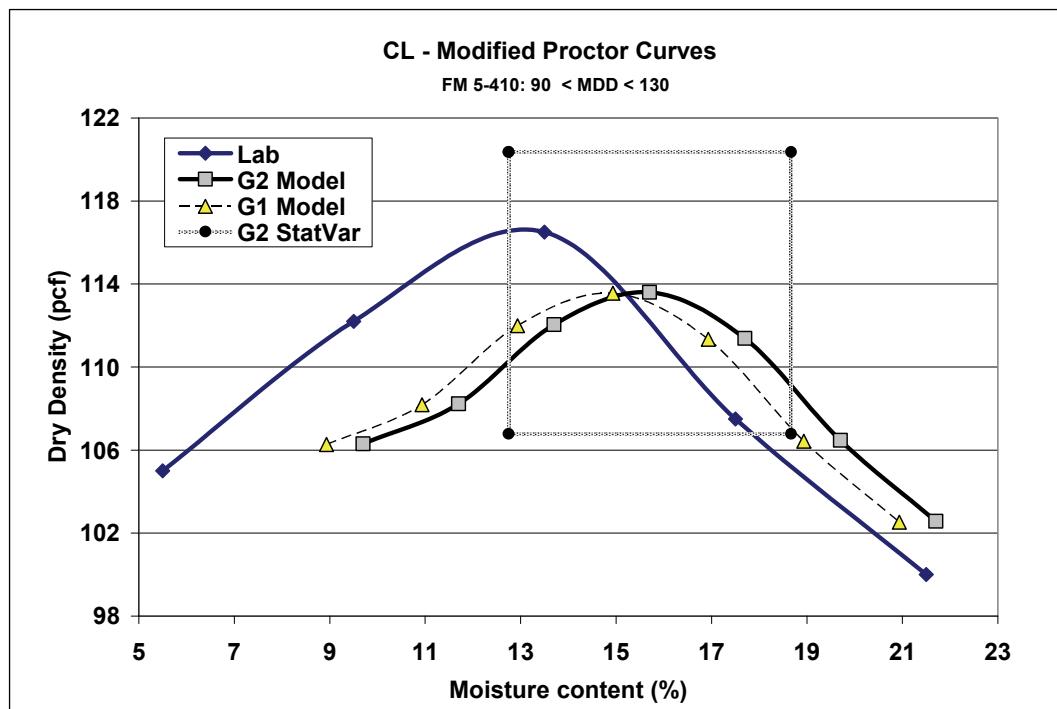
CL - Modified Proctor Curves
FM 5-410: 90 < MDD < 130

CL - Standard Proctor Curves
FM 5-410: No suggestion for MDD

Sandy Clay: Modified and Standard Proctor Compaction Curves with G1 and G2 Correlations

Silty Clay: Modified and Standard Proctor Compaction Curves with G1 and G2 Correlations

Coarse Silty-Sand: Modified and Standard Proctor Compaction Curves
with G1 and G2 Correlations
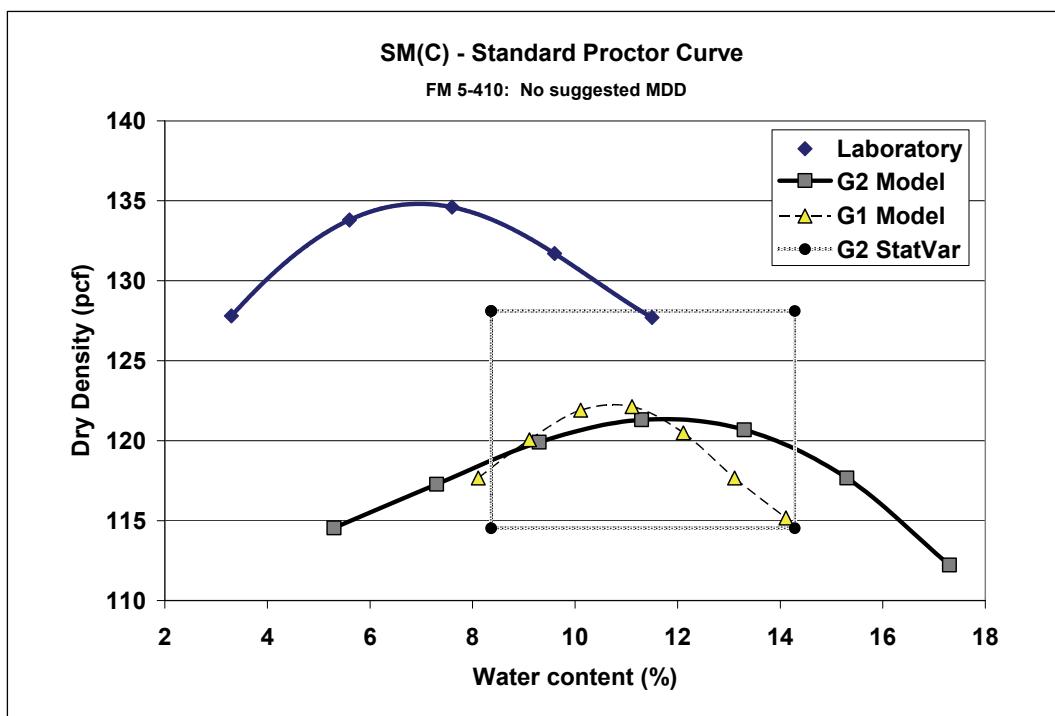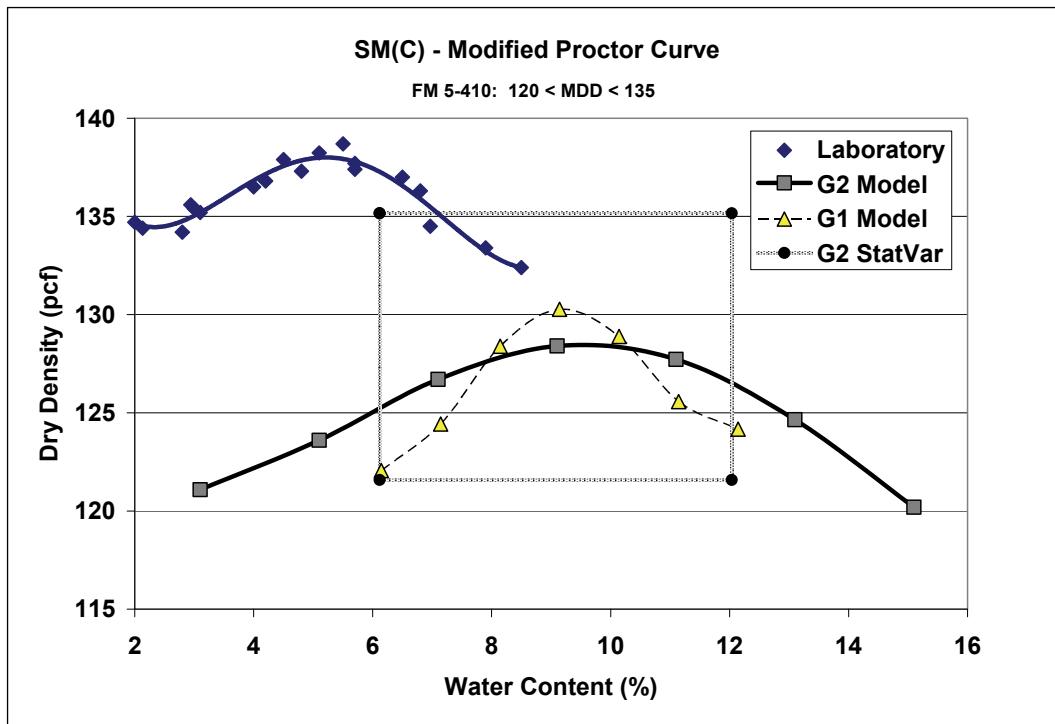
Fine Silty-Sand: Modified and Standard Proctor Compaction Curves with G1 and G2 Correlations
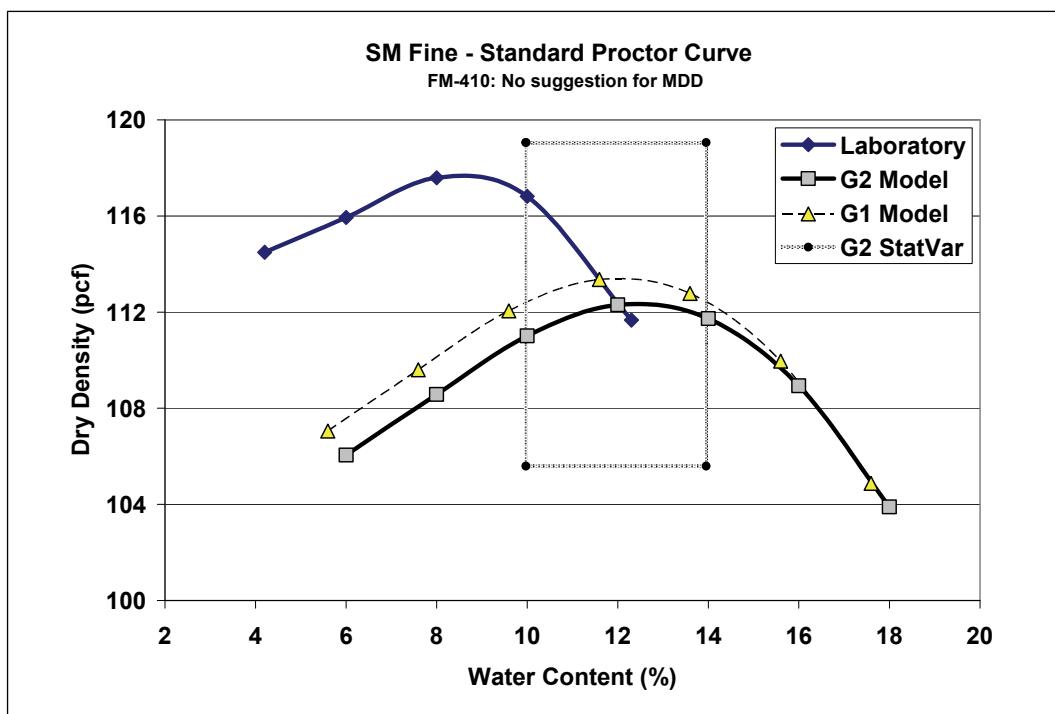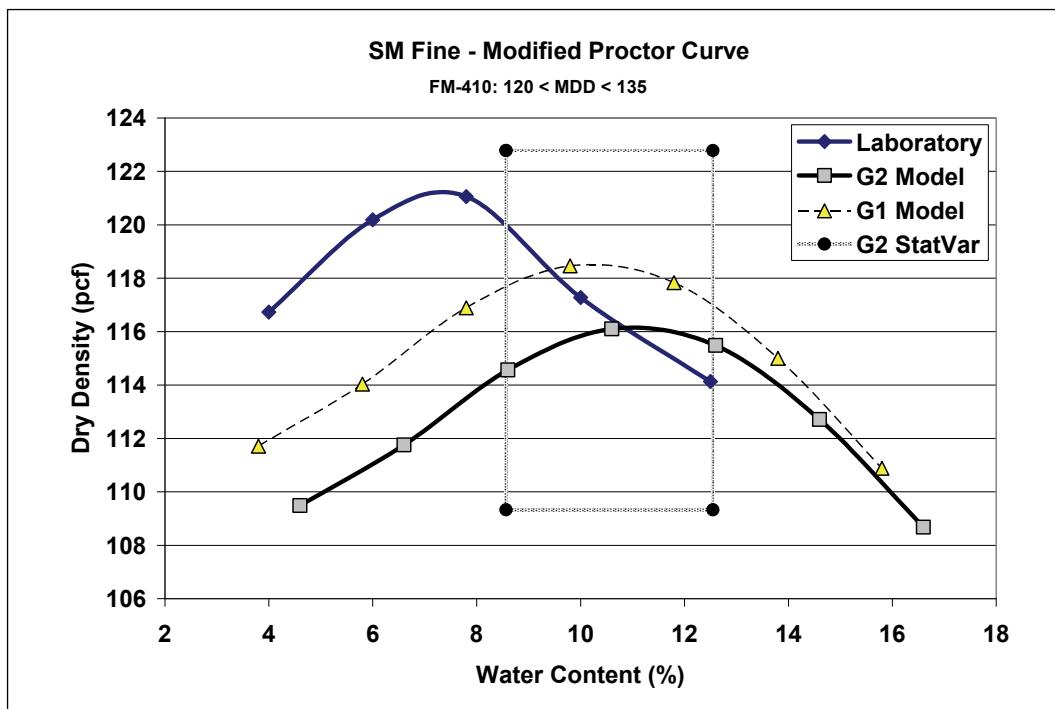
Concrete Sand: Modified and Standard Proctor Compaction Curves with G1 and G2 Correlations
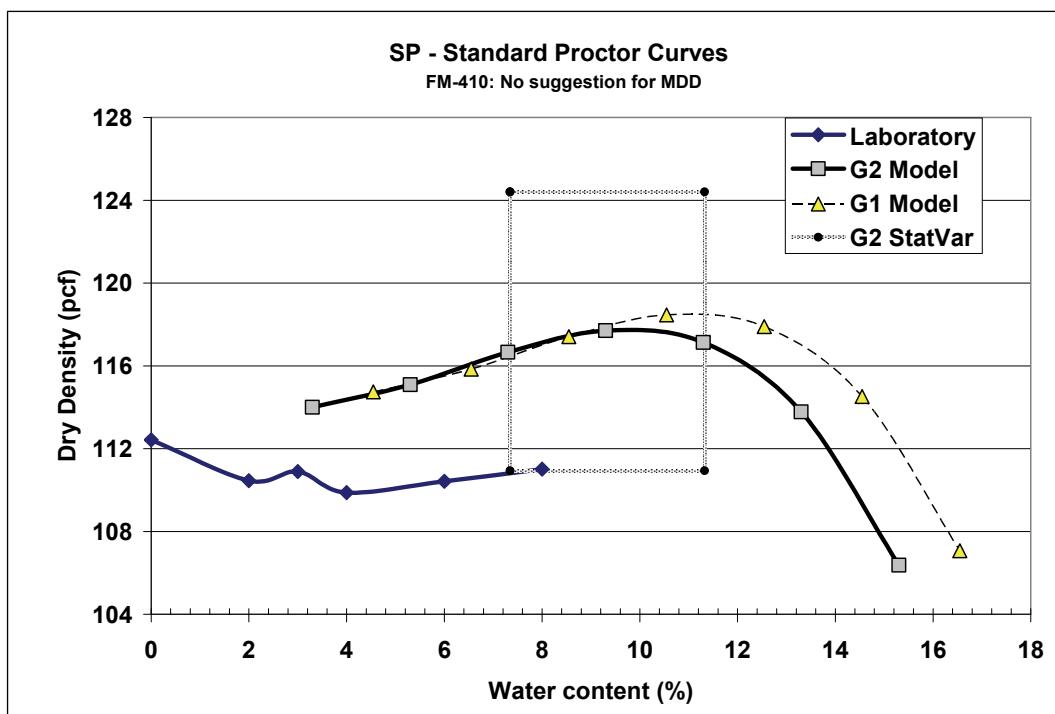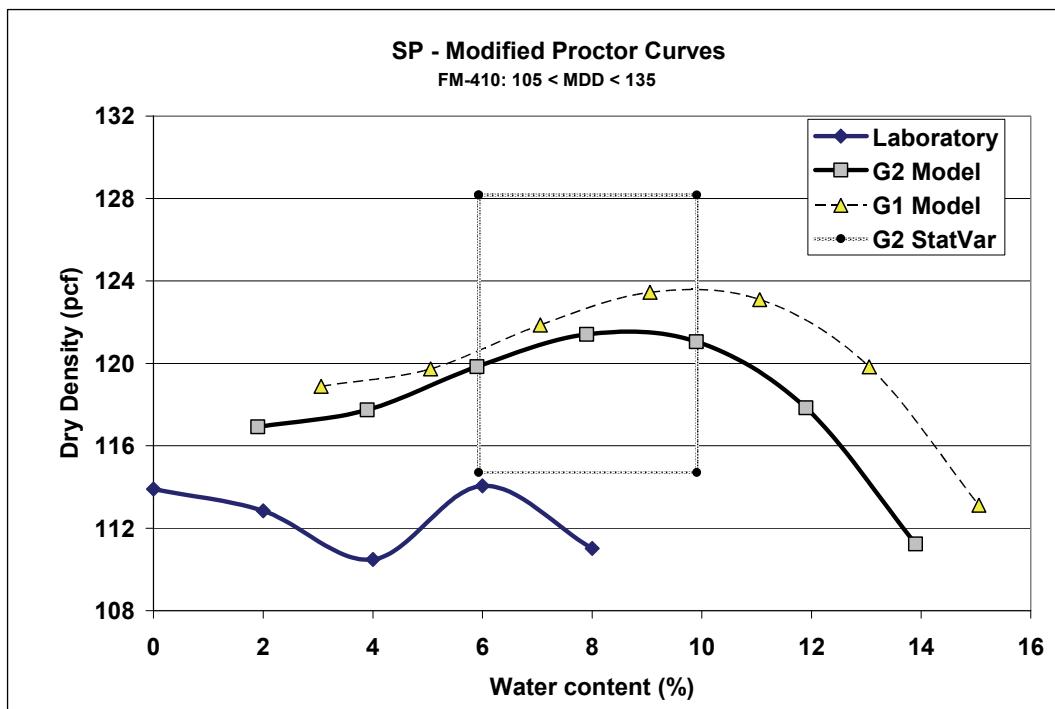
Appendix C: California Bearing Ratio Data

Fat Clay: Modified and Standard CBR Curves with G1 and G2 Correlations

CH - Unsoaked Modified CBR Response
CBR < 15 (FM 5-410)

CH - Unsoaked Standard CBR Response
CBR < 15 (FM 5-410)
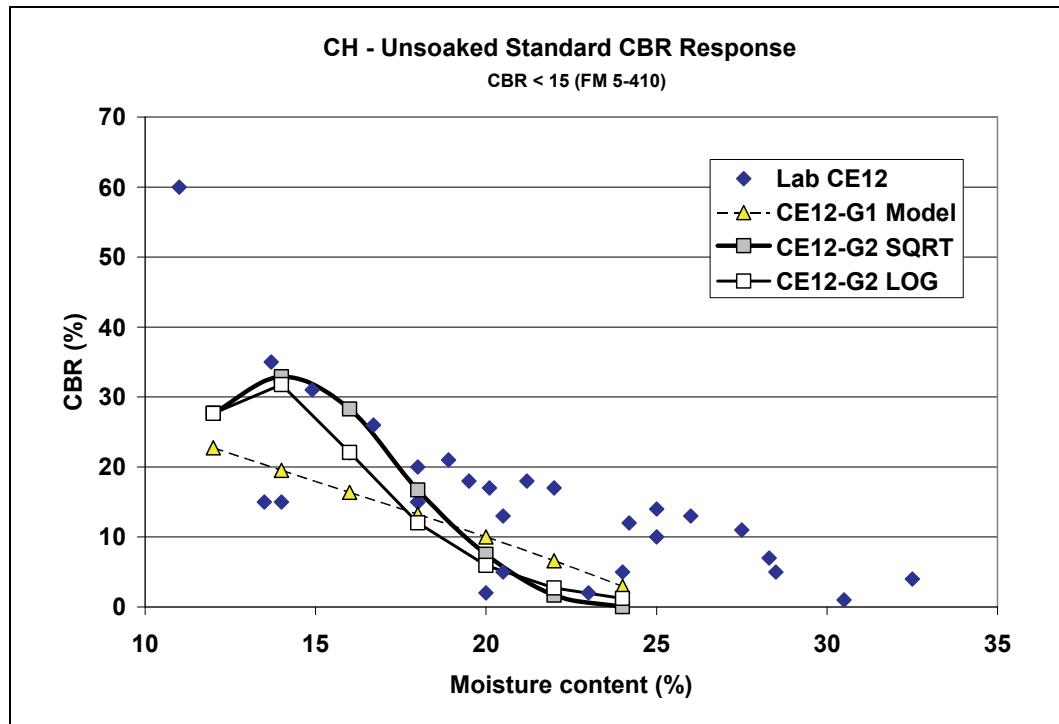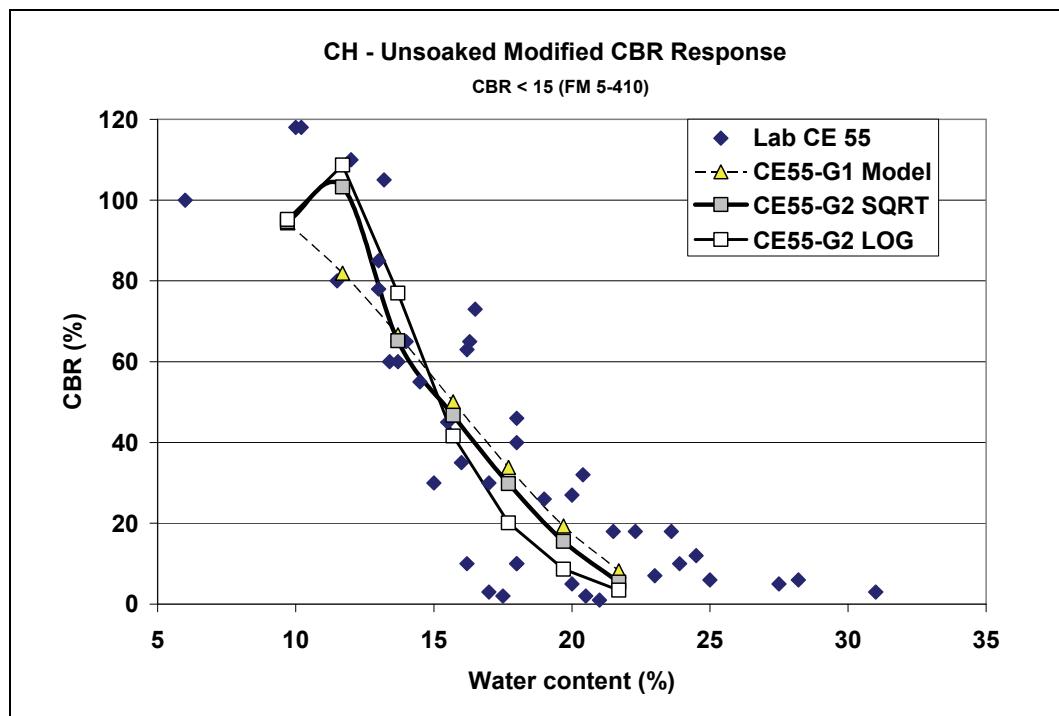
Lean Clay: Modified and Standard CBR Curves with G1 and G2 Correlations

Sandy Clay: Modified and Standard CBR Curves with G1 and G2
Correlations

Silty Clay: Modified and Standard CBR Curves with G1 and G2
Correlations

CL-ML Unsoaked Modified CBR Curve

CBR < 15 (FM 5-410)

CL-ML Unsoaked Standard CBR Curve

CBR < 15 (FM 5-410)

Coarse Silty-Sand: Modified and Standard CBR Curves with G1 and G2 Correlations

Fine Silty-Sand: Modified and Standard CBR Curves with G1 and G2 Correlations

Concrete Sand: Modified and Standard CBR Curves with G1 and G2 Correlations

SP - Unsoaked Modified CBR Comparison

10 < CBR < 40 (FM 5-410)

Legend: CE55-Laboratory, CE55-G1 Model, CE55-G2 SQRT, CE55-G2 LOG

X-axis: Water content (%)
Y-axis: CBR (%)

SP - Unsoaked Standard CBR Comparison

10 < CBR < 40 (FM 5-410)

Legend: CE12-Lab, CE12-G1 Model, CE12-G2 SQRT, CE12-G2 LOG

X-axis: Water content (%)
Y-axis: CBR (%)

Appendix D: Rapid Soils Analysis Kit Software Instruction Manual

This is a copy of the user's manual that is included with the RSAK. The user's manual is presented as a series of screenshots taken from the SoilClassification.exe software included with the RSAK that describes the operation of the program in the context of determining moisture content and soil classification.

1. Clicking on the new button to add a new site will automatically move the user to the next step. Selecting a site from the list allows the option of removing the site from the database or making changes (such as adding a new test date) to the site. To remove the site, click on the remove button. If a site has been selected, click on the next button at the bottom of the screen to move to the next step. Clicking the cancel button will exit the program.
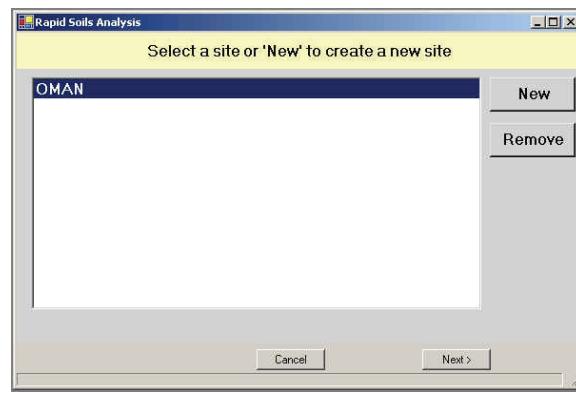
2. Enter the name of the site either by typing it directly into the text box provided or spelling it using the simulated keyboard. After entering the name, click on the next button at the bottom of the screen to move to the next step. Click on the back button to move to the previous step. Click on the cancel button to exit the program.
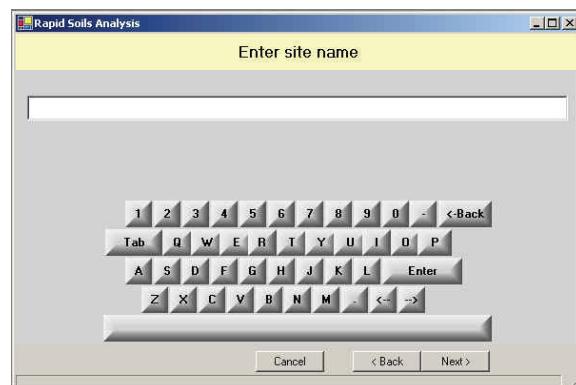
3. Clicking on the new button to add a new test date will automatically move the user to the next step. Selecting a test from the list allows the option of removing the test date from the database or viewing results from tests performed on that date. To remove the test date, click on the remove button. If a test date has been selected, click on the next button at the bottom of the screen to move to the tests page.
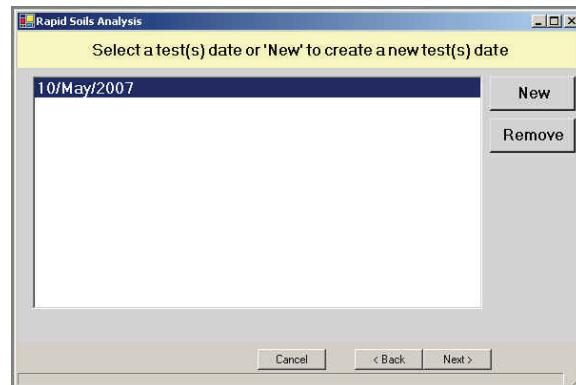
4. Enter the date of the new tests by selecting the month and date using the calendar. By default, the current computer date is selected. After selecting the date, click on the next button at the bottom of the screen to move to the next step.
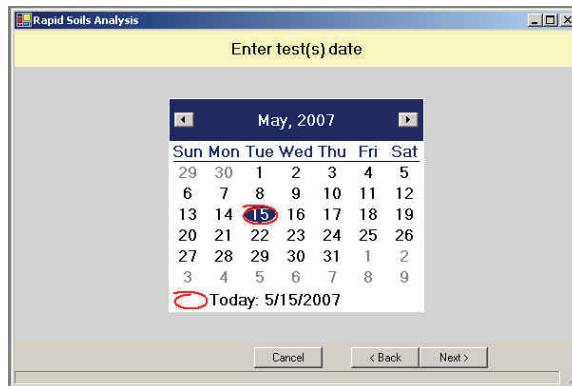
5. Clicking on the new button to add a new test will automatically move the user to the next step. Selecting a test from the list allows the option of removing the sample from the database or viewing the available results from the test. To remove the test, click on the remove button. If a test has been selected, click on the next button at the bottom of the screen to move to the results page.
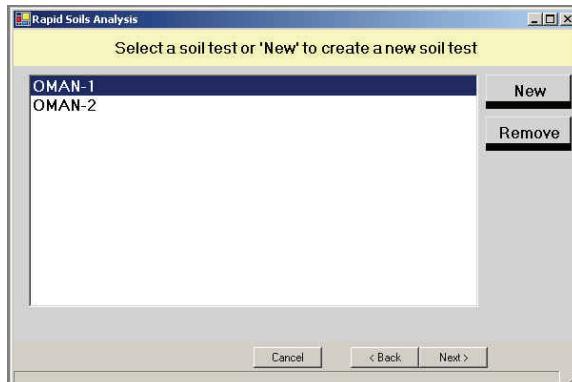
6. Available results appear on a green background. Results that are not available appear on a red background. Click on the option button to display one of the available results. Click on the back button to move backwards to the list of available tests.
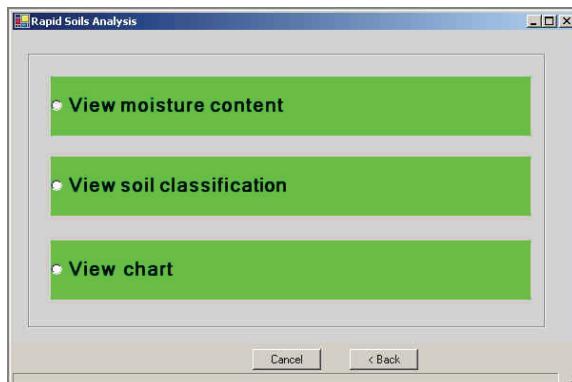
7. Clicking the option for moisture content displays the results of the moisture content test. The moisture content test may be performed on its own or as part of a soil classification test. Click on the back button to move backwards to the list of available results.
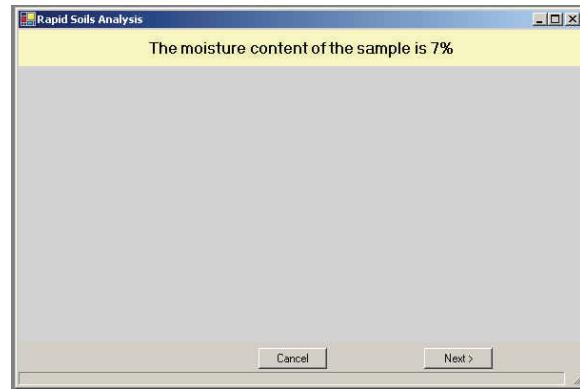
8. Clicking the option for soil classification displays the USCS classification result. Click on the back button to move backwards to the list of available results.
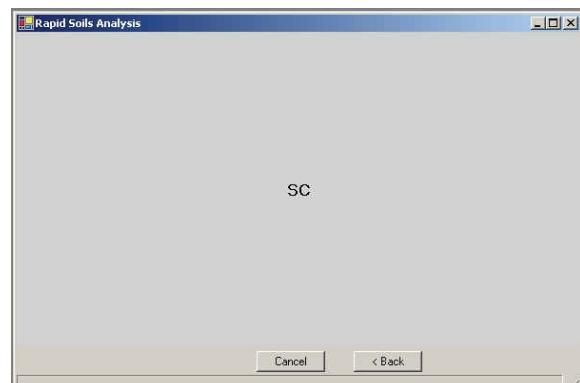
9. Clicking the chart option displays a chart displaying various results of the soil test. Click on the back button to move backwards to the list of available results.
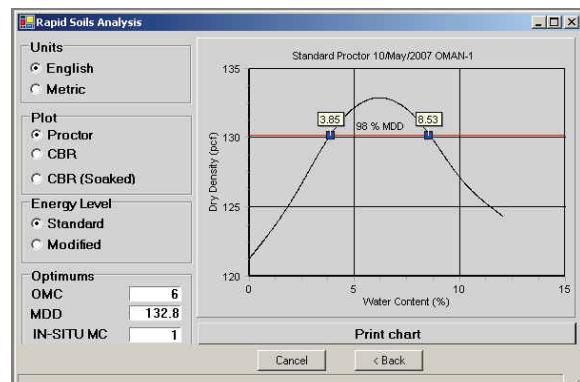
10. Enter an identifier for the new test either by typing it directly into the text box provided or spelling it using the simulated keyboard below the text box. After entering the identifier, click on the next button at the bottom of the screen to move to the next step.
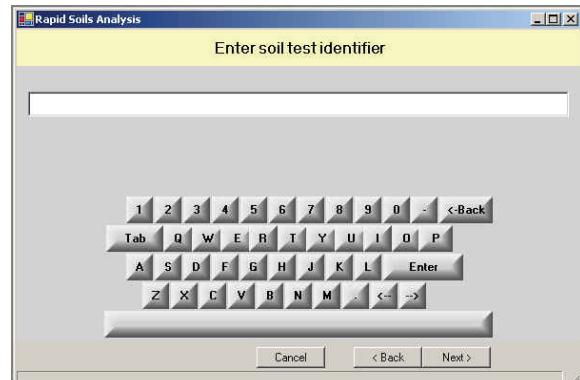
11. Enter the military time the soil sample was taken either by typing it directly into the text boxes provided or spelling it using the simulated keyboard below the text boxes. After entering the time, click on the next button at the bottom of the screen to move to the next step.
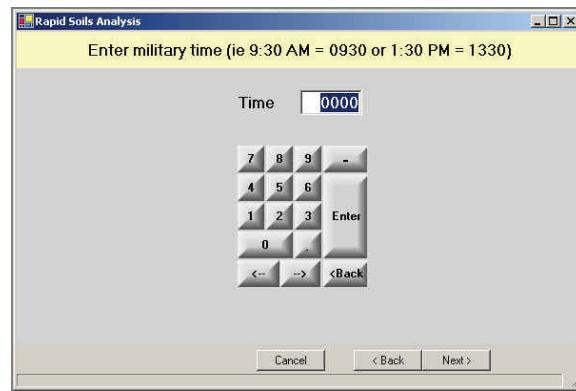
12. Enter the coordinates where the sample was taken either by typing it directly into the text boxes provided or spelling it using the simulated keyboard below the textboxes. After entering the coordinates, click on the next button at the bottom of the screen to move to the next step.
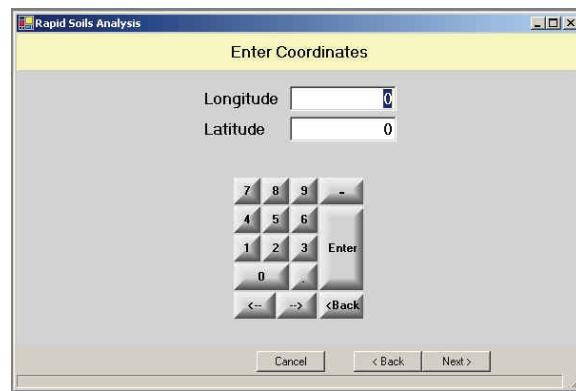
13. Begin the moisture content test by clicking the next button.
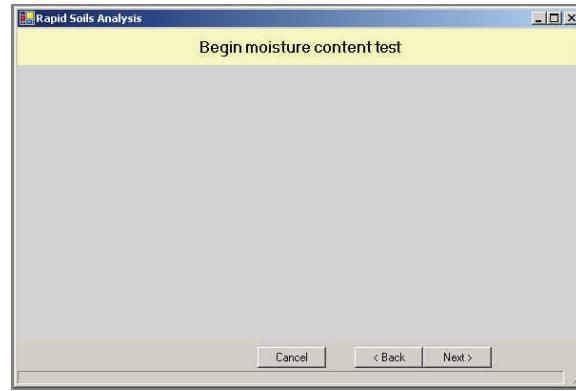
14. Weigh the empty sample bowl and enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the text box. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
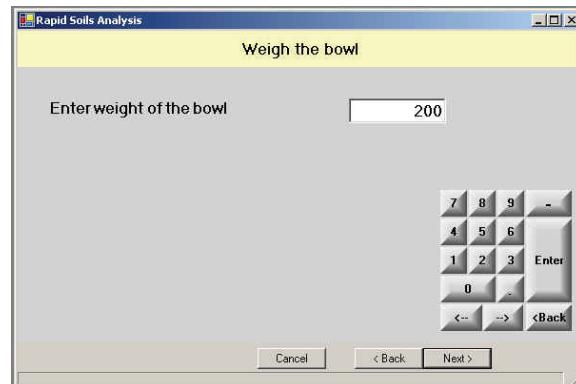
15. Place a moist sample weighing between 200 and 300 g in the empty sample bowl. Weigh the bowl and sample and enter the weight either by typing it directly into the text box provided or using the simulated keyboard to the lower right of the textbox. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
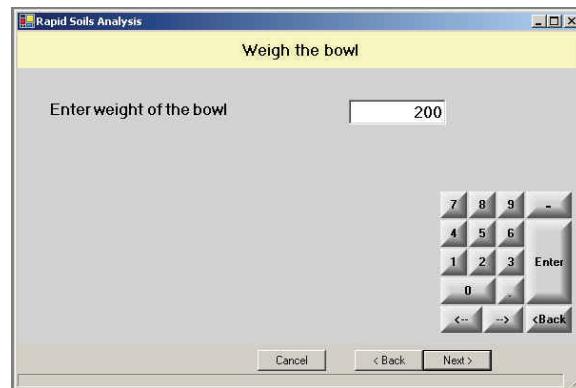
16. Place the bowl containing the moisture sample in the microwave along with the brick from the RSAK and dry for 1 min on high. With gloves (it may be hot) remove the bowl containing the sample and weigh it. Enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the textbox. Note: The weight of the bowl and sample must be between the empty weight of the bowl and the original weight of the bowl and sample. After entering the weight, click on the next button at the bottom of the screen to move to the next step.

17. Stir the sample with a spatula thoroughly and put it back in the microwave along with the brick from the RSAK. Dry it again, for 1 min. Carefully (it may be hot) remove the bowl containing the sample and weigh it. Enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the textbox. Note: The weight of the bowl and sample must be between the empty weight of the bowl and the previously dried weight of the bowl and sample. After entering the

weight, click on the next button at the bottom of the screen to move to the next step. If the percent change in the previous weight and current weight is greater than 1%, the sample will have to be dried again for 1 min. This must be repeated as long as the reduction in weight is greater than one percent after each drying. After the weight is entered each time, the relative change is displayed in the list box to the right. Click on the next button to move to the next step.

18. Once the relative change between weights has reduced to less than one percent, the moisture content will be displayed. Click the next button to move to the next step
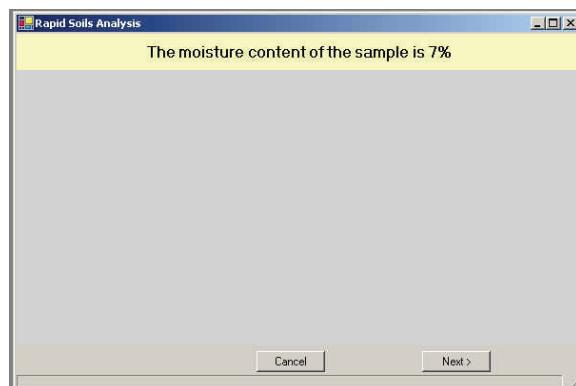
19. Click the yes button to save the sample moisture content test results or no to just move to the next step. Click the next button to move to the next step or the finished button to exit the program.
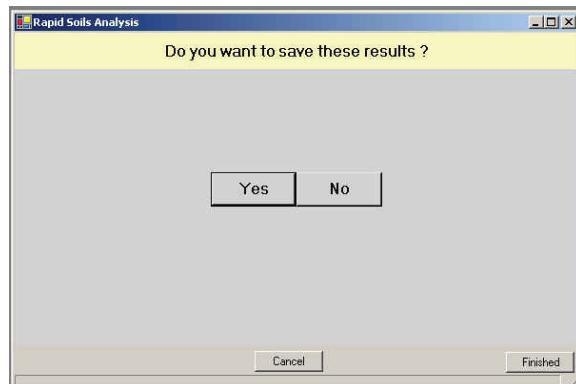
20. Click the yes button to move on to the soil classification test or no to return to the tests list. If no, then the moisture content will be saved and no classification data will be associated with that sample. Click the finished button to exit the program.
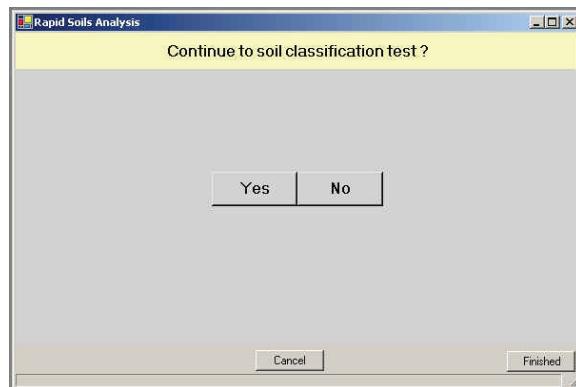
21. Click the yes button to confirm the soil classification test will not be performed. Click no to reconsider and perform the soil classification test. Click the finished button to exit the program.
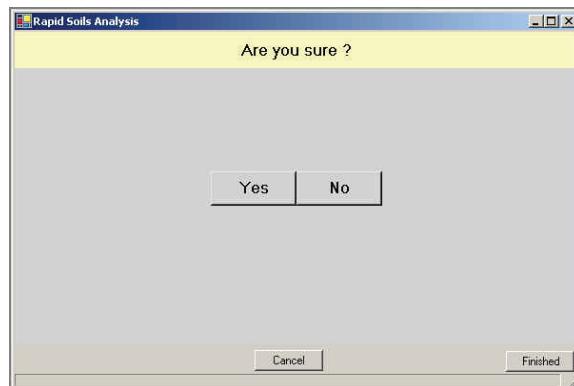
22. Crush the dried soil sample using the mortar and pestle. This may take several minutes to accomplish. Once this is accomplished, click the next button to move to the next step or the finished button to exit the program.
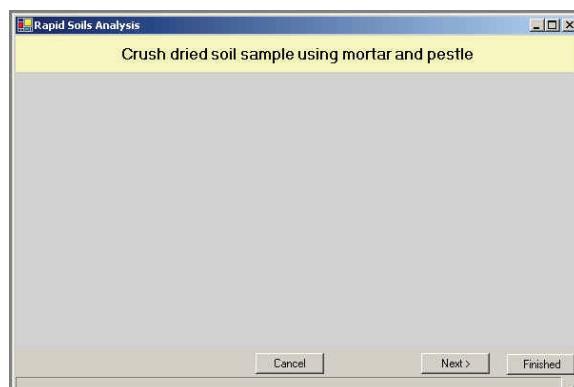
23. Weigh a new empty sample bowl and enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the textbox. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
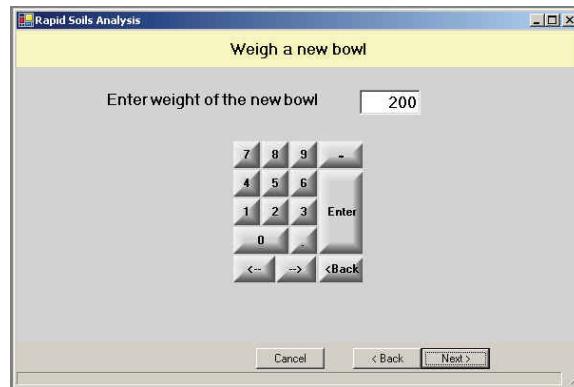
24. Place the microwave-dried sample weighing between 200 and 300 g in the empty sample bowl. Weigh the bowl and sample and enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the textbox. After
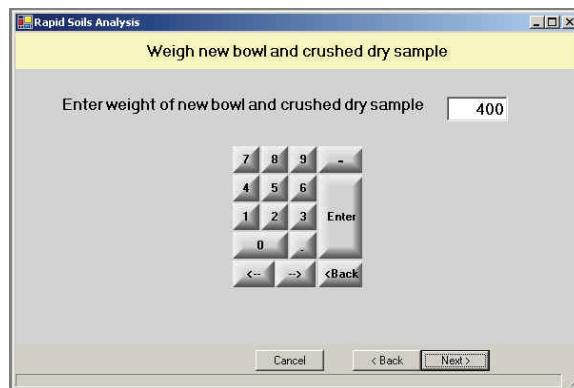
entering the weight, click on the next button at the bottom of the screen to move to the next step.

25. Split the crushed and dried sample with the splitter to produce two equal samples each less than 150 g each. Click the next button to move to the next step or the finished button to exit the program.
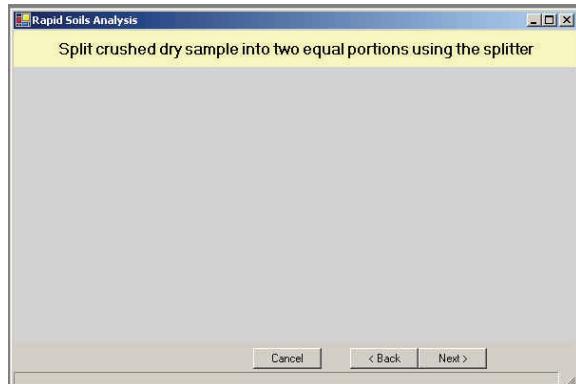
26. Weigh any soil retained on the splitter. Enter the weight either by typing it directly into the textbox provided or using the simulated keyboard below the textbox. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
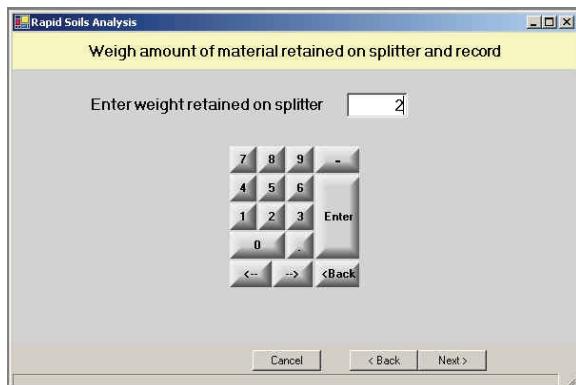
27. Weigh each sieve empty and the pan and record the weight of each in the adjacent textboxes. Enter the weights either by typing it directly into the textboxes provided or using the simulated keyboard to the right of the textboxes. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
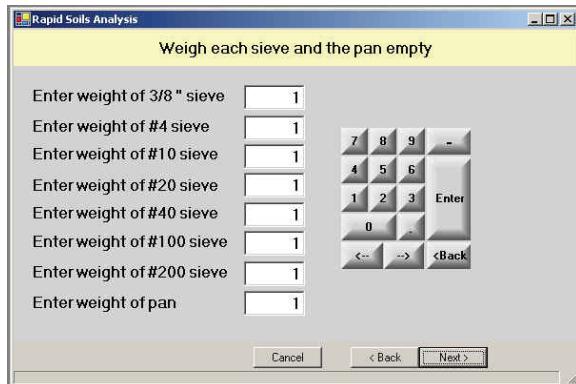
28. From the split sample weigh out approximately half the contents of the first pan (75 g or less) and enter the weight in the textbox. Enter the weight either by typing it directly into the textbox provided or using the simulated keyboard below the textbox. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
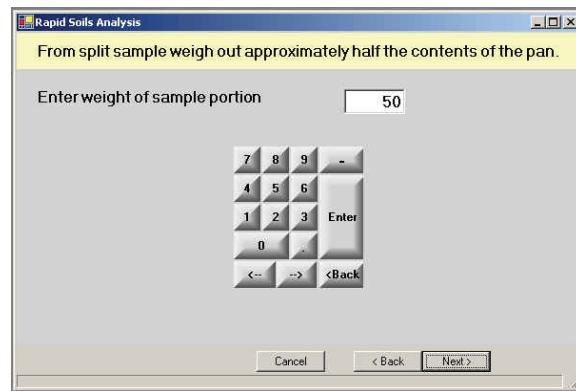
29. Pour the weighed sample from the previous step into the sieve stack and shake for 4 min. After completing this step, click on the next button at the bottom of the screen to move to the next step.
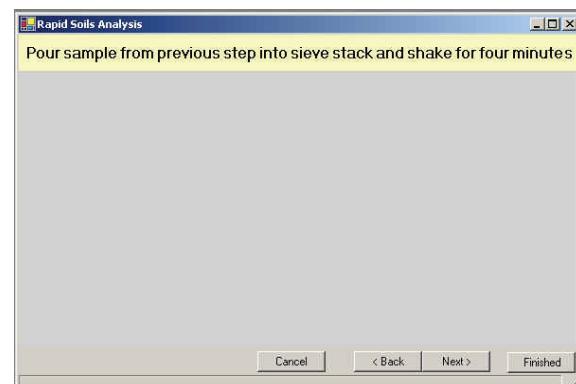
30. Weigh each sieve and the soil it retained. Weigh the pan and the soil it contains also. Record the weight of each in the adjacent textboxes. Enter the weights either by typing it directly into the textboxes provided or using the simulated keyboard to the right of the textboxes. After entering the weights, click on the next button at the bottom of the screen to move to the next step.
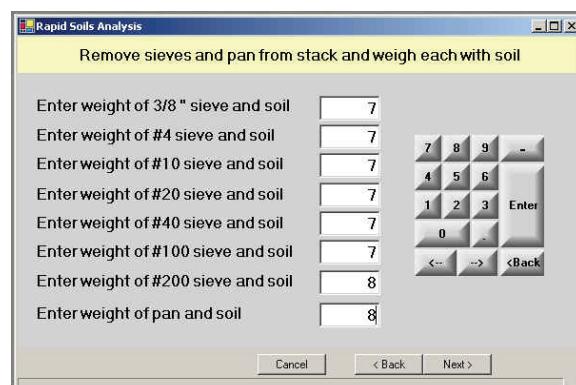
31. If the total of the soil weights on the sieves exceeds the sample weight, there are two choices. Clicking the yes button confirms the weights entered were correct. In which case, the sample weight will be adjusted to match the total of the soil weights on the sieves. Clicking the no button, the weights on the sieves may be adjusted or corrected as needed. If the weights on the sieves did not exceed the sample weight, clicking the yes button simply confirms the weights are correct. If the no button is clicked the weights of the sieves and retained sample may be adjusted or corrected.
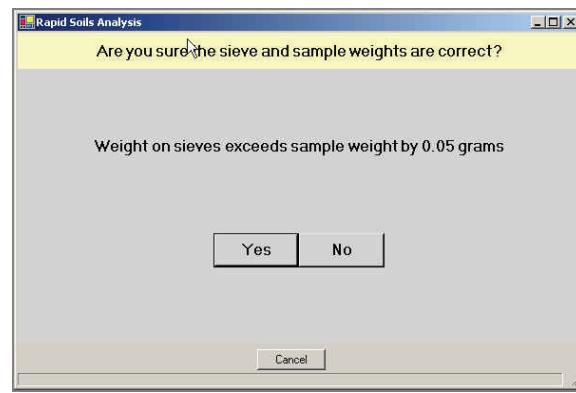
32. This indicates the results of the test were invalid. If the actual percent loss was close to 2%, the results can be accepted by clicking yes. If the yes button is clicked, the remaining half of the pan's sample will be weighed and tested using the sieve shaker. If the no button is clicked, the test will begin again using the sample in the remaining (second) pan.
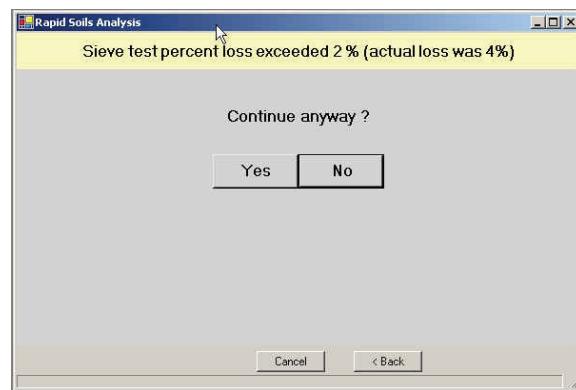
33. If the results of testing on the two halves of neither split sample are accepted, the soil test has failed and must be done again with a new sample. Click on the next button at the bottom of the screen to move to the next step.
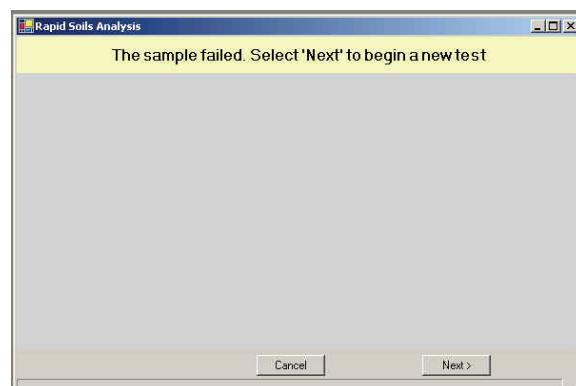
34. To begin the plastic limit test, moisten the soil passing the No. 40 sieve and attempt to roll 1/8 threads. If successful, clicking the yes button will allow the user to determine the plastic limit. If not, clicking the no button will move to the end of the plastic limit test and the plastic limit will be set to zero.
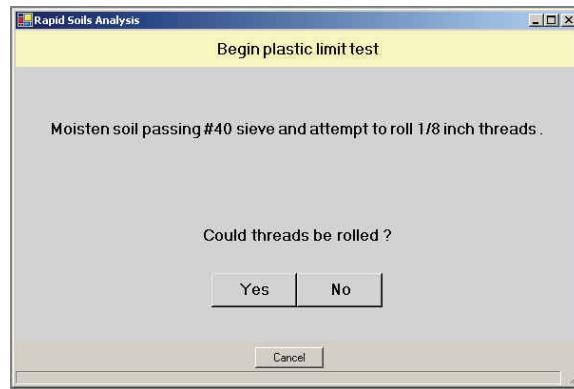
35. For the plastic limit threads, weigh a new empty sample bowl and enter the weight either by typing it directly into the text-box provided or using the simulated keyboard to the lower right of the textbox. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
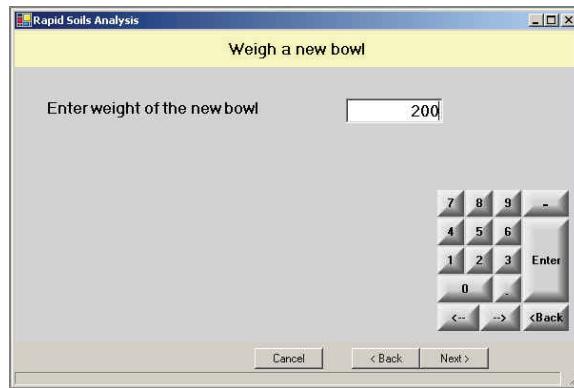
36. Weigh the new bowl and sample (plastic limit threads) and enter the weight either by typing it directly into the text-box provided or using the simulated keyboard to the lower right of the textbox. After entering the weight, click on the next button at the bottom of the screen to move to the next step.
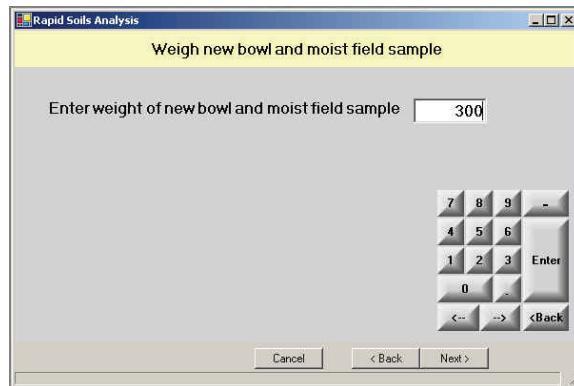
37. Place the bowl containing the threads in the microwave along with the brick from the RSAK and dry for 1 min on high. Carefully (it may be hot) remove the bowl containing the sample and weigh it. Enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the textbox. Note: The weight of the bowl and sample must be between the empty weight of the bowl and the original weight of the bowl and sample. After entering the weight, click on the next button at the bottom of the screen to move to the next step.

38. Stir the sample with a spatula thoroughly and put it back in the microwave along with the brick from the RSAK. Dry it again, for 1 min. Carefully (it may be hot) remove the bowl containing the sample and weigh it. Enter the weight either by typing it directly into the textbox provided or using the simulated keyboard to the lower right of the textbox. Note: The weight of the bowl and sample must be between the empty weight of the bowl and the previously dried weight of the bowl and sample. After entering the weight, click on the next button at the bottom of the screen to move to the next step. If the percent change in the previous weight and current weight is greater than 1%, the sample will have to be dried again for 1 min. This must be repeated as long as the reduction in weight is greater than one percent after each drying. After the weight is entered each time, the relative change is displayed in the list box to the right. Click on the next button to move to the next step.

39. Once the sample has been successfully dried, decide if the soil texture is clayey or silty. If unable to determine soil texture, select unknown (takes an average). Click next at the bottom of the screen to move to the next step.
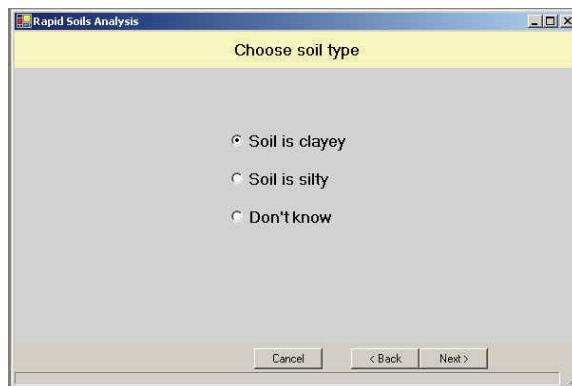
40. Once the plastic limit has been determined, click the next button at the bottom of the screen to move to the next step.
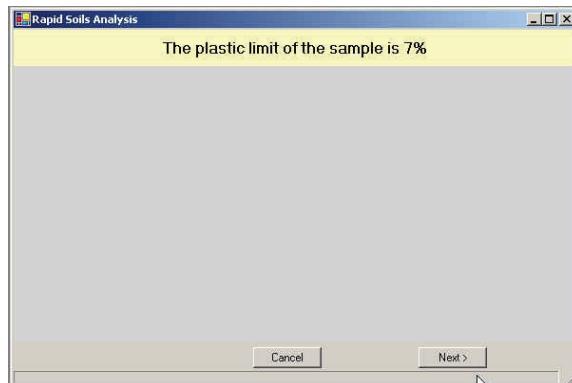
41. Once the samples have been successfully tested and the plastic limit is determined, the resulting soil type will be displayed. Click on the next button at the bottom of the screen to move to the next step.
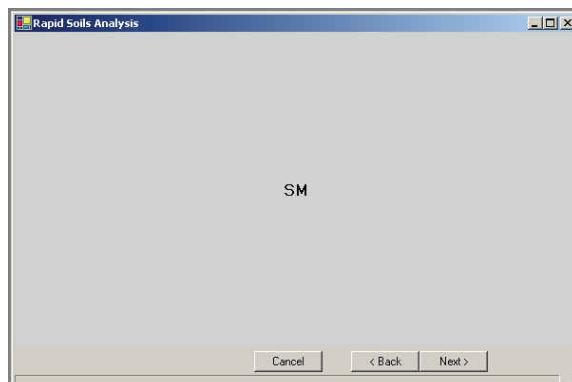
42. Click the yes button to save the test results and move to the next step or click no and the test results will not be saved. Click the next button to move to the next step.

43. The plot shows the moisture-density and CBR curves based on the classification and plastic limit values. Click Print chart to print the curve. Click on the next button at the bottom of the screen to move to the next page. Click on the finished button to exit the program.
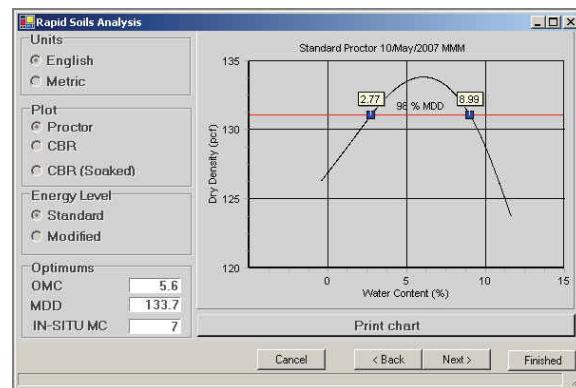
44. At this point, the choices are to return to the sites, tests dates, or soil test screen.
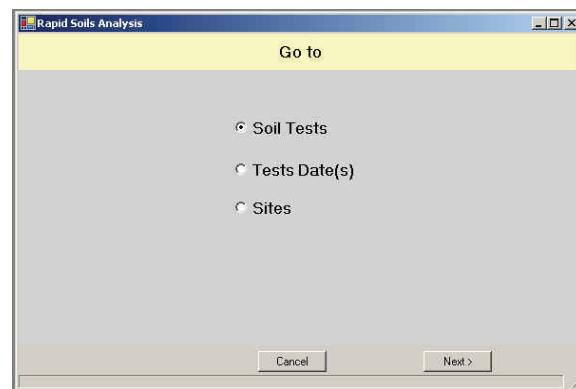
Appendix E: Procedure for Performing a Soils Analysis

1. Select an area for field sample and record site, date, test name and latitude/longitude for later reference
       (enter values in program)
2. Obtain a moist field sample of between 200 and 300 g
       (enter value in program)
3. Dry field sample in microwave
4. Weigh dried field sample
       (enter value in program)
5. Crush dried sample with mortar and pestle for coarse soils or coffee grinder for soils passing the No. 40 sieve prior to splitting
6. Pour field sample over splitter dividing it into two equal portions
7. Weigh amount of material retained on splitter
       (enter value in program)
8. Ensure that the split sample weighs no more than 150 g dry.
9. Weigh each sieve in stack empty (eight entries) (clean sieves with brushes if dirty)
       (enter values in program)
10. Take one pan from the splitter and weight out approximately half the soil
       (enter value in program)
11. Pour sample into sieve stack and sieve for 4 min
12. Remove sieves from stack
13. Weigh each sieve with soil (eight entries)
       (enter value in program)
14. Place all material on the No. 100, No. 200 and Pan sieves into a container for use in Plastic Limit Test
15. Clean sieves with brushes
16. Weigh out remaining soil left in splitter pan from Step 10
       (enter value in program)
17. Pour sample into sieve stack and sieve for 4 min
18. Remove sieves from stack
19. Weigh each sieve with soil (eight entries)
       (enter values in program)
20. Place all material on the No. 100, No. 200 and pan sieves into container used in Step 14.

21. Conduct Plastic Limit Test on soil saved from Steps 14 and 18
    (follow steps in program)
22. Determine whether the soil in Step 21 is Clayey or Silty using textural classification methods
    (check appropriate button)
23. Note the soil classification

Appendix F: Index Parameters for G1 and G2 Proctor Curve and G1 CBR Curve Correlations

The following tables illustrate the coefficients required to generate a poly-nomial curve to trace the moisture-density response and the CBR and soaked CBR response for a given soil classification. Care should be taken when extending the relationships beyond the upper and lower bound moisture contents, as the fourth order polynomials no longer behave appropriately.

MODIFIED Database of Coefficients for Proctor Curve						Allowable MC	
Soil Type	A	B	C	D	Constant	Min	Max
CH	2.0E-05	-1.0E-04	-0.0024	0.0016	1	-6	6
CL	6.0E-05	-4.0E-05	-0.0044	-0.0013	1	-6	6
CL-ML	0	0	-0.0028	-0.0087	1	-6	6
ML	1.0E-05	-2.0E-05	-0.002	-0.0042	1	-5	5
SM	2.0E-05	-8.0E-05	-0.0024	0.0023	1	-6	6
SC-SM	8.0E-04	1.0E-04	-0.0133	0.0018	1	-3	3
SC	5.0E-05	1.0E-05	-0.0048	0.0014	1	-6	6
SP-SC	9.0E-06	-2.0E-04	-0.002	0.0033	1	-6	6
SW-SC	9.0E-05	-2.0E-04	-0.005	0.0038	1	-5	5
SP-SM	2.0E-05	4.0E-05	-0.0021	-0.0016	1	-6	3
SW-SM	9.0E-05	-2.0E-04	-0.005	0.0038	1	-5	5
SP	9.0E-06	-2.0E-04	-0.002	0.0033	1	-6	6
SW	9.0E-05	-2.0E-04	-0.005	0.0038	1	-5	5
GC	2.0E-04	2.0E-04	-0.007	-0.0003	1	-5	4
GC-GM	4.0E-05	-2.0E-05	-0.0034	0.0001	1	-5	5
GM	4.0E-05	-2.0E-05	-0.0034	0.0001	1	-5	5
GP-GM	4.0E-05	-2.0E-05	-0.0034	0.0001	1	-5	5
GP-GC	4.0E-05	-2.0E-05	-0.0034	0.0001	1	-5	5
GP	-2.0E-03	-1.9E-03	-0.0037	0.0095	1	-5	3
GW-GM	2.0E-05	-7.0E-04	-0.003	0.006	1	-5	3
GW	-3.0E-05	-9.0E-04	-0.0056	0.0084	1	-5	3
GW-GC	3.0E-05	-8.0E-05	-0.0034	0.0008	1	-5	4

STANDARD Database of Coefficients for Proctor Curve						Allowable MC	
Soil Type	A	B	C	D	Constant	Min	Max
CH	2.0E-05	-3.0E-05	-0.0022	0.0028	1	-6	6
CL	3.0E-05	-9.0E-05	-0.0031	0.0026	1	-6	6
CL-ML	0	0	-0.003	-0.0176	1	-5	5
ML	7.0E-05	-6.0E-06	-0.0051	-0.0014	1	-5	5
SM	8.0E-06	-1.0E-04	-0.0021	0.002	1	-6	6
SC-SM	3.0E-04	3.0E-04	-0.0079	-0.0061	1	-3	3
SC	5.0E-05	2.0E-05	-0.0039	0.0012	1	-6	6
SP-SC	-2.0E-06	-2.0E-04	-0.0017	0.0018	1	-6	6
SW-SC	2.0E-04	3.0E-04	-0.0076	-0.0006	1	-5	5
SP-SM	0	-2.0E-04	-0.0029	-0.0056	1	-6	3
SW-SM	2.0E-04	3.0E-04	-0.0076	-0.0006	1	-5	5
SP	-2.0E-06	-2.0E-04	-0.0017	0.0018	1	-6	6
SW	2.0E-04	3.0E-04	-0.0076	-0.0006	1	-5	5
GC	8.0E-05	9.0E-05	-0.0054	0.0014	1	-5	4
GC-GM	2.0E-04	-4.0E-05	-0.0068	0.0033	1	-4	4
GM	2.0E-04	-4.0E-05	-0.0068	0.0033	1	-4	4
GP-GM	2.0E-04	-4.0E-05	-0.0068	0.0033	1	-4	4
GP-GC	2.0E-04	-4.0E-05	-0.0068	0.0033	1	-4	4
GP	-3.0E-05	-1.0E-03	-0.0092	-0.00001	1	-5	3
GW-GM	8.0E-05	2.0E-05	-0.0046	0.0034	1	-5	3
GW	1.0E-03	-7.0E-04	-0.0184	0.0148	1	-5	3
GW-GC	8.0E-05	2.0E-05	-0.0046	0.0034	1	-5	4

MODIFIED Database of Coefficients for CBR						Allowable MC	
Soil Type	A	B	C	D	Constant	Min	Max
CH	0	0.0324	0.0337	-8.3423	50.097	-6	6
CL	-0.0313	0.365	0.7288	-19.15	52.133	-6	6
CL-ML	0	0.1491	-0.1419	-15.878	63.928	-5	5
ML	0	0.0725	0.0039	-13.485	62.506	-5	5
SM	0.1061	0.5507	-4.5657	-18.71	84.651	-6	6
SC-SM	0	1.3768	-3.1228	-33.105	96.918	-3	3
SC	0.0761	0.6611	-3.7008	-25.176	87.293	-6	6
SP-SC	0	-0.205	-2.8822	-1.6231	98.504	-6	6
SW-SC	0	0	-1.5345	-9.0646	114.65	-5	5
SP-SM	0.0396	0.7257	1.7793	-11.535	49.839	-6	3
SW-SM	0	0	-1.5345	-9.0646	114.65	-5	5
SP	0	-0.205	-2.8822	-1.6231	98.504	-6	6
SW	0	0	-1.5345	-9.0646	114.65	-5	5
GC	0.3121	2.4414	-4.6629	-40.817	77.432	-5	4
GC-GM	0	-0.1688	-2.3734	-12.922	127.76	-5	5
GM	0	-0.1688	-2.3734	-12.922	127.76	-5	5
GP-GM	0	-0.1688	-2.3734	-12.922	127.76	-5	5
GP-GC	0	-0.1688	-2.3734	-12.922	127.76	-5	5
GP	0	-1.2944	-11.061	-18.869	156.36	-5	3
GW-GM	0	-1.4291	-1.9525	6.8509	224.72	-5	3
GW	0	-1.2524	-12.122	-13.735	152.61	-5	3
GW-GC	0	-0.1361	-3.0162	-17.195	120.33	-5	4

STANDARD Database of Coefficients for CBR						Allowable MC	
Soil Type	A	B	C	D	Constant	Min	Max
CH	0	-0.0017	-0.0112	-1.5892	13.239	-6	6
CL	0	0.0206	0.1013	-3.6554	12.672	-6	6
CL-ML	0	0	0	-2.871	5.5475	-5	5
ML	0	0.0067	0.0167	-3.0524	18.136	-5	5
SM	0.0093	0.0825	-0.543	-3.9214	21.505	-6	6
SC-SM	0	0.0163	0.05	-3.2569	12.764	-3	3
SC	0	0.0328	-1.007	-4.7838	16.415	-6	6
SP-SC	0	-0.0378	-0.7955	-2.4907	33.508	-6	6
SW-SC	0	0.2943	-1.9021	-10.921	43.981	-5	5
SP-SM	0.0025	0.0344	-0.2573	-3.0676	21.501	-6	3
SW-SM	0	0.2943	-1.9021	-10.921	43.981	-5	5
SP	0	-0.0378	-0.7955	-2.4907	33.508	-6	6
SW	0	0.2943	-1.9021	-10.921	43.981	-5	5
GC	0	0.2705	0.7824	-7.8252	10.419	-5	4
GC-GM	0	-0.0341	-0.2736	-4.5632	26.177	-4	4
GM	0	-0.0341	-0.2736	-4.5632	26.177	-4	4
GP-GM	0	-0.0341	-0.2736	-4.5632	26.177	-4	4
GP-GC	0	-0.0341	-0.2736	-4.5632	26.177	-4	4
GP	0	-0.0133	-0.1183	5.0679	63.734	-5	3
GW-GM	0	0.0603	-0.6607	-6.1386	29.332	-5	3
GW	0	-0.8341	-0.8823	-8.1325	46.361	-5	3
GW-GC	0	0.0603	-0.6607	-6.1386	29.332	-5	4

MODIFIED Database of Coefficients for Soaked CBR						Allowable MC	
Soil Type	A	B	C	D	Constant	Min	Max
CH	-0.0011	-0.0165	-0.0205	0.6236	4.1652	-6	6
CL	0	0.1335	-1.094	-2.843	26.474	-6	6
CL-ML	0	0.1335	-1.094	-2.843	26.474	-5	5
ML	0	0.1335	-1.094	-2.843	26.474	-5	5
SM	0.0401	0.2766	-2.378	-8.798	62.618	-6	6
SC-SM	0	2.4375	-3.9062	-30.172	71.758	-3	3
SC	0	-0.0634	-1.514	-1.1782	41.522	-6	6
SP-SC	0	-0.1308	-1.7446	0.4913	70.03	-6	6
SW-SC	0	0.5076	-2.1887	-9.1482	42.483	-5	5
SP-SM	-0.0571	-1.6309	-13.567	-17.638	127.9	-6	3
SW-SM	0	0.5076	-2.1887	-9.1482	42.483	-5	5
SP	0	-0.1308	-1.7446	0.4913	70.03	-6	6
SW	0	0.5076	-2.1887	-9.1482	42.483	-5	5
GC	0.2203	0.689	-4.8362	-8.3515	34.624	-5	4
GC-GM	0	0.6775	-3.626	-11.431	82.17	-5	5
GM	0	0.6775	-3.626	-11.431	82.17	-5	5
GP-GM	0	0.6775	-3.626	-11.431	82.17	-5	5
GP-GC	0	0.6775	-3.626	-11.431	82.17	-5	5
GP	0	-3.3766	-30.39	-52.662	84.351	-5	3
GW-GM	0	0.4608	-2.0254	-8.674	50.674	-5	3
GW	0	2.3611	-9.4439	-18.069	118.07	-5	3
GW-GC	0	0.4608	-2.0254	-8.674	50.674	-5	4

STANDARD Database of Coefficients for Soaked CBR						Allowable MC	
Soil Type	A	B	C	D	Constant	Min	Max
CH	-0.0072	-0.0577	0.1185	1.773	6.79	-6	6
CL	0	0.0518	0.4401	-1.314	10.809	-6	6
CL-ML	0	0.0518	0.4401	-1.314	10.809	-5	5
ML	0	0.0518	0.4401	-1.314	10.809	-5	5
SM	0.005	0.0046	-0.7025	-0.9233	21.866	-6	6
SC-SM	0	0	-0.0904	-1.7646	9.2606	-3	3
SC	0	-0.0169	-0.3891	-0.9633	12.232	-6	6
SP-SC	0	-0.0723	-1.0013	0.2422	31.173	-6	6
SW-SC	0	-0.1161	-7.4002	-13.405	109.4	-5	5
SP-SM	-0.0013	-0.0967	-1.3031	-1.8549	31.807	-6	3
SW-SM	0	-0.1161	-7.4002	-13.405	109.4	-5	5
SP	0	-0.0723	-1.0013	0.2422	31.173	-6	6
SW	0	-0.1161	-7.4002	-13.405	109.4	-5	5
GC	0	0.0973	-0.0733	-1.7656	5.3528	-5	4
GC-GM	0	0.0544	-1.6267	-3.1304	28.65	-4	4
GM	0	0.0544	-1.6267	-3.1304	28.65	-4	4
GP-GM	0	0.0544	-1.6267	-3.1304	28.65	-4	4
GP-GC	0	0.0544	-1.6267	-3.1304	28.65	-4	4
GP	0	-0.06667	-9.3333	-19.833	32.333	-5	3
GW-GM	0	0.065	-1.004	-2.7628	17.418	-5	3
GW	0	-0.0104	-3.096	2.8287	55	-5	3
GW-GC	0	0.065	-1.004	-2.7628	17.418	-5	4

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14. ABSTRACT
The ability to determine the construction requirements for soil without the need to conduct laboratory testing is essential to performing a contingency design. Until now, only subjective field analysis techniques satisfied this requirement, and their results fail to provide tangible numeric data that can be used to determine moisture-density and California bearing ratio (CBR) design criteria. This report describes the rapid soils analysis kit (RSAK) developed during the period November 2003–May 2007 under the Joint Rapid Airfield Construction Program. The RSAK includes compact field test instruments that are easily transported to provide an immediate measure of soil moisture, grain size distribution (GSD), and plastic limit. An accompanying software program incorporates the numeric data generated from the soils kit, classifies the soil, and uses multiple regression routines based on a statistical analysis of a large database of soil properties to predict optimum moisture content and maximum dry density for the soil of interest. Built-in, higher order regression equations allow the user to visualize complete moisture-density curves for varying compaction energies as well as soaked and unsoaked CBR as functions of water content for the constructed condition of the soil. The moisture-density curve and CBR strength represent the critical data necessary to enable contingency design and construction of highways and airfields.

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